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Warrants for Right-Turn Flashing Yellow Arrow Signal Phases

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WARRANTS FOR RIGHT-TURN FLASHING YELLOW ARROW SIGNAL PHASES

by

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Abstract

The right-turn flashing yellow arrow (FYA) signal phasing is a new signal practice in the United States. The *Manual on Uniform Traffic Control Devices* MUTCD (2009) allocates a signal phasing section for the right-turn FYA, which requires a four-section head FYA signal. It supports multiple phases' indications that guide the motorist through permissive, protected, and/or permissive/protected phases. For this dissertation, I investigated three permissive right-turn FYA signal phases in various traffic conditions and signal timing circumstances. The first permissive right-turn FYA signal phase is the tight-turn on impeding through (RTOIT) taking place during the cross-street through traffic movement. The second permissive right-turn FYA signal phase occurs during the opposing left-turn approach movement and so is called the right-turn on impeding left (RTOIL). The third permissive right-turn phase is a right-turn on through green impeded only by the side street pedestrians called the right-turn on adjacent through (RTOAT). I aimed to develop warrants leading to efficient implementation of permissive right-turn FYA signal phases based on microsimulation analysis. I developed multinomial logit models to establish a decision support system that predicts the efficiency attributes of the permissive right-turn FYA signal phases.

Keywords: Right-turn FYA, Permissive Right-turn Phases, Blank out Signs, Right-turn on Red, Right-turn on Circular Green

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CHAPTER 1: INTRODUCTION AND RESEARCH TASKS

Introduction

A flashing yellow arrow is a new signal standard phasing practice seeing widespread used throughout the United States that has become well understood by the road's users. The roads' users in central Florida pass through a large number of left-turn FYA signals. The right-turn FYA signal is the latest signal phasing practice in the United States, and there are few signalized intersections implementing this new practice. The protected/permissive FYA phasing allows the use of a protected only mode (PO), permissive only mode, protected/permissive mode (PPRT), or a combination of the three signal indications modes. It changes depending on the traffic conditions and time of day. A protected right turn has the right of way (ROW) to proceed through an intersection where conflicting vehicles or pedestrians are prohibited. A permissive right-turn relies only on an acceptable gap between the impeding traffic to maneuver, including bicycles and pedestrians (FHWA 2015, Hurwitz, Monsere et al. 2018). Factors including sight distance restriction, approach crash rate, percentage of heavy traffic and acceptable stopped delay, and operation speed of an approach affect the signal indication mode selection (HCM 2010).

The right-turn FYA phase is implemented only on a four-section head signal, which can tolerate the four phasing modes described in the MUTCD. The phasing operation mode is defined by the time-of-day traffic condition. It could display permissive only mode, PPRT, FYA, or PO phase mode. The four indications change depending on which intersection approach has the right-of-way movement. For instance, when the cross-street through traffic or the opposing left-turn traffic has the right of way to proceed through the intersection, the right-turn shall be permitted to display FYA signal indication. Right-turn traffic has to yield to the pedestrians crossing the side street or the main street during the adjacent lane and impeding through movements. The right-turn phase displays a protected green right-turn arrow simultaneously with the movement of the crossing left-turn approach movement. To prevent conflicting traffic, the U-turn should be prohibited for the crossing left-turn approach.

I studied three permissive right-turn FYA signal phases in different traffic approaches, signal timing plans, and pedestrian circumstances. The permissive right-turn FYA signal phases consist of two right turns on adjacent lanes through red and a right turn on adjacent lanes through green. The first right-turn on red phase, right turn on impeding through (RTOIT), is impeded by the cross-street through traffic and any pedestrian crossing the main street. The second right-turn on red phase, right turn on impeding left (RTOIL), is impeded only by the opposing left-turn traffic. The right-turn on adjacent green phase, right turn on adjacent through (RTOAT), occurs simultaneously with the adjacent lane green phase and is impeded only by pedestrian activity crossing the side street. This research warrants for the right-turn FYA signal based on microsimulation analysis. The guidelines and models obtained from statistical design of experiments (DOEs) helped me assess the efficient implementation of a permissive protected right-turn PPRT FYA signal for a single exclusive right-turn lane.

I used the microsimulation outcomes to establish decision support systems. The response, average maximum right-turn throughput (MRTT) per cycle, was categorized into categorical variables representing the efficiency attributes of the FYA signal phases. The observations were extracted from the DOEs' scenarios in a set of random seeds replications. I took this step to develop decision support systems that allow decision makers to assess the efficient application of a permissive FYA signal during RTOIT, RTOIL, and RTOAT phases using a set of significant parameters. The multinomial logit (MNL) models' results accurately replicated the DOEs' outcomes.

Research Objective

From this research, I sought to develop guidelines for efficient implementation of a right-turn FYA signal at an exclusive single right-turn lane. I investigated three permissive right-turn FYA signal phases to warrant and predict the efficiency attributes of a right-turn FYA signal. Thus, I proposed the following questions:

- Does the permissive RTOIT FYA phase during the impeding through phase at signalized intersections work properly and efficiently?
- Does the permissive RTOIL FYA phase during the impeding left-turn phase at signalized intersections work properly and efficiently?
- Does the permissive RTOAT FYA phase during the adjacent through phase at signalized intersections work properly and efficiently?
- How does blank-out, right-turn treatment differ or play a key role in the PPRT phasing practice warrants?
- Can the current evaluation tools (microsimulation software) be used, complimented with field data, to investigate the new phasing practices of the studied systems?
- What are the significant factors derived from the previous studies that affect the performance of traffic in dedicated right turning lanes? Can these factors, coupled with a statistical design of the experiment, be used to predict the performance of the new right-turn FYA signal phases?

- Would an appropriate statistical design of the experiment warrant switching from the permissive FYA phasing mode to a red indication arrow complimented with a no-turn-on-red blank-out sign (BOS) in certain impeding conditions?

Research Scope

Developing warrants for the permissive right-turn FYA signal phase is the goal of this research. I undertook procedures to appropriately warrant an efficient FYA signal phase and develop functional guidelines based on microsimulation analysis. This was based on both hypothetical and real site geometry designs and listed DOEs input data (traffic vehicle features and signal timing parameters). The signalized intersection was designed with a dedicated right-turn lane, an exclusive right-turn, four-section head signal, suitable sight distance, and exclusive cross-street left-turns signals. The exclusive left-turn signal was designed to allow the display of the protected right-turn overlap phase. Thus, the cross-street U-turn is prohibited to allow the right-turn movement simultaneously with the movement of the cross street left-turn traffic.

CHAPTER 2: LITERATURE REVIEW

2.1 Right-turn Phasing Background

The PPRT phasing allows the use of protected only mode, permissive only mode, protected/permissive mode, or a combination of the three signal indications mode. It changes depending on the traffic level conditions during the day. A protected right turn has the right of way (ROW) to proceed through an intersection where the conflicting vehicles or pedestrians are prohibited (FHWA 2015, Hurwitz, Monsere et al. 2018). A permissive right turn relies only on an acceptable gap in the impeding traffic, which includes bicycles and pedestrians (FHWA 2015, Hurwitz, Monsere et al. 2018). Factors including sight distance restriction, approach crash rate, percentage of heavy traffic and acceptable stopped delay, and operation speed of an approach significantly affect the signal indication mode selection (HCM 2010).

The *Manual on Uniform Traffic Control Devices* (MUTCD (2009) lists four major signal indications for right-turn movements at a signalized intersection:

1. Permissive Only Mode: right-turn traffic makes a turn when a circular green signal indication, a flashing right-turn yellow arrow signal indication, or a flashing right-turn red arrow signal indication arises after a motorist yields to pedestrians and opposing traffic if any.
2. Protected Only Mode: the right-turn traffic makes a turn when a green right arrow signal indication arises.
3. Protected/Permissive Mode: Both protected and permissive modes occur on an approach movement during the same cycle.

4. Variable Right-turn Mode: the mode changes during different times of day from the protected only mode and/or the protected/permissive mode and/or the permissive only mode. This operation relies on the traffic conditions.

2.2 Right-Turn Lane Geometry Related Studies

A protected right turn requires an exclusive right-turn lane that separates the right-turn movement from an adjacent through (FHWA 2015 a, Hurwitz, Monsere et al. 2018). According to the National Cooperative Highway Research Program (NCHRP) Report 279, Neuman (1985) studied right-turn lanes in urban areas and found that right-turn volumes, right-turning rear end crashes, and/or pedestrian crossing volumes were significant factors that justified the need of right-turn treatments, whereas in the rural area speed, right turn volumes, and the land use types were the significant factors (Varma, Ale et al. 2008). Neuman (1985)warranted the right-turn lanes on four-lane high speed roadways based on the percentage of right-turn vehicles to the number of through vehicles during the peak hour. The road design manual published by the Minnesota Department of Transportation MNDOT (2015) states that the design of exclusive right-turn lanes in urban area was considered functional if the construction were economically beneficial. Several factors were considered such as the amount of ROW needed, type of terrain, and land use areas. An exclusive right-turn lane was found to efficiently improve the overall operation and safety of the intersection (ODOT 2012, Hurwitz, Monsere et al. 2018)

The design of turning roadways and channelization is essential in intersection design (AASHTO 2011, Hurwitz, Monsere et al. 2018). *Channelization* is defined as the separation of "conflicting traffic movements into definite paths or travel by traffic islands or pavement markings to facilitate the orderly movements of both vehicles and pedestrians" (AASHTO 2011). AASHTO

(2011) stated that the channelization design improves the signalized intersection operational efficiency and safety by providing clear guidelines to motorists. Dixon, K. K., Hibbard, J. L., & Nyman, H. (1999) studied 17 randomly chosen signalized intersections and performed a preliminary crash history from the viewpoint of the geometric design of such signalized intersections. The authors analyzed five types of entrance right-turn lane treatments and six exit right-turn lane treatment configurations (see Figure 1). Five scenarios were studied, which varied in the following factors: the existence of an exclusive right-turn lane, the existence of and type of an island, and the control type. The additional use lanes, islands, and control traffic devices at signalized intersections were observed clearly to improve the operational level and safety at the right-turn lanes (Dixon, Hibbard et al. 1999, Rodegerdts, Nevers et al. 2004) .

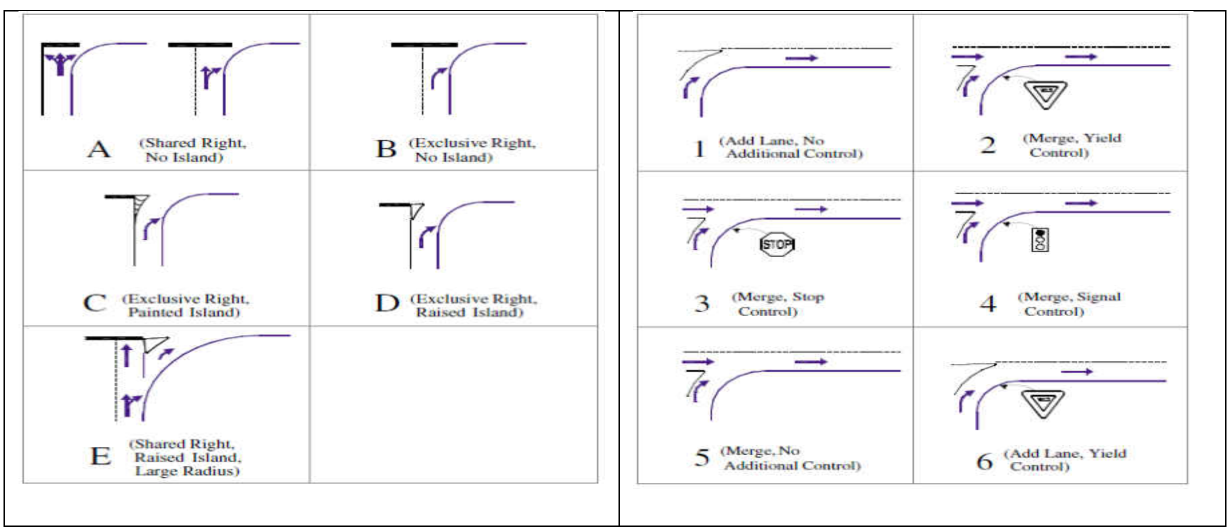

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Figure 1. Entrance and treatment (source: Dixon et al. 1999)

2.3 Right-Turn Phasing Related Studies

Signalized intersections are considered the focal point of the highway transportation system. Right-turn movement is an essential movement affecting the signalized intersection's performance. PPRT signal involves two permissive right turns on red: RTOIT and RTOIL phases and a right turn during the adjacent through lane; RTOAT and a protected phase during the overlap phase.

The Washington State Department of Transportation's Design Manual has documented various aspects of the right-turn phasing. It stated that phasing should be dedicated when there is an exclusive right-turn lane. The manual suggested the dedicated right turn lane phasing is operated the same way as the left-turn phasing. The dedicated right-turn lane would be operated as protected/permissive or PO phasing mode (WSDOT 2017). When right-turn overlap phasing is considered, the right-turn phasing indication relies on the operating mode of every indication section:

- Permissive: permissive mode allows right-turn movement when the adjacent lane faces a circular green indication.
- Protected: the protected right-turn indication arises when the complementary cross street protected left-turn phase exists or with the through phase associated with the right turn.

The traffic design manual of Tennessee State TDOT (2016) assigned a section for right-turn phasing. It included three right-turn signal phasing indications: permissive mode only, PO mode, and protected/permissive mode. It stated that a dedicated right-turn lane exists when a separate right-turn signal indication is used. The manual states that the right-turn treatment is defined by three factors for each approach:

1. Lane usage (shared, exclusive, or channelized),
2. The right turn on red acceptance (allowed or prohibited), and
3. Right-turn movement mode type (permissive, protected, or both).

2.4 Right-Turn Overlap Phasing Overview

The overlap right-turn phase is a signal indication in which the right turn traffic makes a turn during a circular green ball during a permissive phase. The protected operation occurs only if the cross street has a protected left-turn phase while the U-turn is prohibited (Perez 1995). The right-turn traffic can make a protected right turn during the protected left-turn movement of the cross street. The right-turn traffic faces a green right arrow because this movement has no conflicting movement when the U-turn of cross streets is prohibited. The overlap phasing requires a five or four section head signal, as illustrated in Figures 2 and 5.

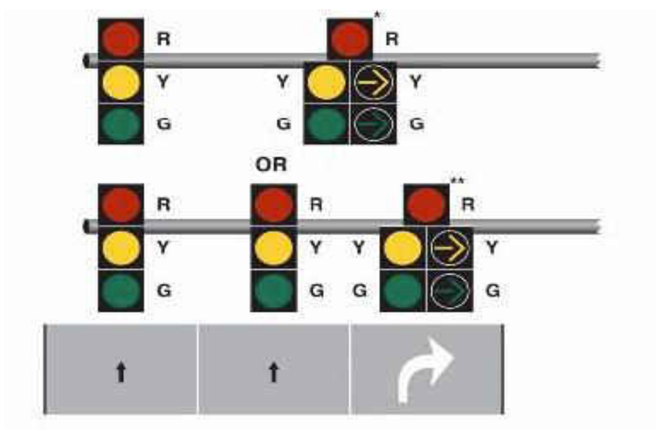


Figure 2. Five-section head signal (source: MUTCD, 2009).

The *California Department of Transportation Traffic Manual* (CAMUTCD 2017) devoted a section for the right-turn phasing. It stated that a right-turn green arrow should be considered where there is a dedicated right-turn lane. The manual suggested that an exclusive permissive lane should be considered when the right-turn traffic volume exceeded 200 vehicles per hour: A right-turn yellow arrow shall be shown following a right turn green arrow when a circular red or a right-turn red arrow is following (CAMUTCD 2017). The *Florida Intersection Design Guide 2015* recommended using a protected right-turn overlap phasing taking place during a complimentary protected left-turn phasing (FHWA 2015). It stated that the right-turn capacity may be increased by displaying such a right-turn arrow simultaneously with the protected left-turn phase and that when the right-turn is in a protected mode phase, U-turns should be prevented for the protected crossing-street left-turn movement to avoid the conflicting traffic (FHWA 2015).

2.4.1 Right-Turn on Red Phasing Overview

Right turn on red (RTOR) allows right-turn traffic to make a right-turn movement after a complete stop during a red phase. In most states, vehicular traffic may turn right on red after a full stop and yield for pedestrian and impeding traffic (FHWA 2015, Herman 2002). Many studies have researched the RTOR and found that allowing right turns on red leads to operational delay reduction, positive environmental effect, and energy consumption reduction (McGee, Stimpson et al. 1976, Herman 2002). Technical Council Committee 4M-20 was established by the Institute of Transportation Engineers to investigate driver behavior on RTORs. The committee found that RTOR maneuvers equal up to 39.2% of all right-turn movements and 40.4% of drivers on RTOR did not come to a full stop before proceeding to the intersection and 95% of right turners on red who had the opportunity to right-turn on red did so (Wagoner 1992, Noyce and Knodler 2017)

The *Manual on Uniform Traffic Control Device* (MUTCD) set six safety cases in which the right turn on red is prohibited and recommended the use of a *No Turn on Red* sign. The right turn on red is prohibited when at least one of the six safety concerns is applied as listed in the (MUTCD 2009):

1. Insufficient sight distance to vehicles approaching from the left or right, if applicable;
2. Intersection geometric design that might lead to unexpected conflicts;
3. An exclusive pedestrian phase;

4. A significant number of pedestrian conflicts with right turn on red traffic, especially if children, elderly pedestrians, or handicapped are involved;
5. More than three right-turn-on red crashes occurred in a twelve months period; and
6. Skewed intersecting roadways that result in difficulty for motorists to observe the approaching traffic coming from their left.

2.4.2 Pedestrian Phasing-Related Studies

The crossing pedestrians at signalized intersections conflict with many traffic maneuvers. The conflicts interact with permissive maneuvers including left-turn, right-turn on a circular green, and right-turn on red at States permitting right-turn on red (RTOR). Pedestrians are usually assigned to cross simultaneously with the through-traffic movement where a vehicle or bicyclist must yield before turning right (FHWA 2015 b). (Hurwitz, Monsere et al. 2018) stated that when exclusive right-turn lanes are designed with high right-turn traffic volumes, this pedestrian phasing practice might not be proper. FHWA (2015 b) recommended exclusive pedestrian phases and prohibition of RTORs with implementation of signs to restrict right-turn motorist movement when pedestrian volume is high (FHWA 2015 b). The RTORs' restriction purpose is to increase pedestrians' safety and reduce the pedestrian crash rate at intersections (FHWA 2015 b). The RTORs operations might be prohibited at certain times of the day (FHWA 2015 b).

A pedestrian walk interval (PWI) must be sufficient to allow pedestrians to start moving (Zegeer, Sandt et al. 2006)see Figure 3). The *Manual on Uniform Traffic Control Devices for Streets and Highways* recommended the walk interval to be at least 7 seconds so that pedestrians can leave the curb or shoulder before the pedestrian clearance time begins. Additionally, the manual suggested that if pedestrian volumes and the crosswalk characteristics do not require a 7-second walk interval, the walk intervals should not be shorter than 4 seconds (MUTCD 2003).

Figure 3. Pedestrian walking symbol signal.

A clearance interval or flashing or *Don't Walk* signal (flashing upraised hand) is a function of the crosswalk length and the pedestrian speed (MUTCD 2003)see Figure 4). The FDW interval should be adequate to ensure that a pedestrian can cross the entire street before the FDW phase vanishes (Zegeer, Sandt et al. 2006). The walking speed is most commonly assumed as a 1.2 m/s (4 ft/s), and slower walking speeds of 1.1 m/s (3.5 ft/s) or even 0.9 m/s (3 ft/s) may be appropriately used at locations where there is a substantial number of elderly people (Zegeer, Sandt et al. 2006). A slower walking speed is recommended by The *Highway Capacity Manual* if the percentage of elderly pedestrians represent 20% or more of the total pedestrian volume using that crosswalk (Zegeer, Sandt et al. 2006, HCM 2010).

Figure 4. Pedestrian flash *Don't Walk* signal.

Boot, Charness et al. (2015) conducted research on pedestrian safety and found that Florida had the highest pedestrian-fatalities rate in the United States from 2008–2011. The authors investigated the driver behavior and comprehension of four pedestrian signs: *No Turn on Red, Yield to Pedestrians, Stop Here on Red*, and *Right on Red Arrow after Stop*. The authors found that drivers presented a high rate of comprehension with the *No Turn on Red* sign, and *Stop on Red, No Turn on Red*, and *Right on Red Arrow after Stop* signs increased the likelihood of comprehension compared to the control group (Boot, Charness et al. 2015).

The *Florida Intersection Design Guide 2015* devoted a section for the need for protected right-turn phasing. The manual stated that most right turns proceed as permitted movement at most signalized intersection approaches when the right turners have to yield to conflicting pedestrians and bicycles. It listed a few cases where protected right-turn arrow phases are recommended. The manual suggested a protected right-turn arrow phase during a portion of the vehicular green to maintain adequate right-turn movement. This phase indication was highly suggested for intersections with very heavy pedestrians traffic and "vehicular green times that exceed pedestrians crossing time requirements" (FDOT 2015). The longer green time can be created by extending the cycle length.

2.5 Flashing Yellow Arrow FYA-Related Studies

Within the last few years, FYA has been used on a number of left-turn lane signals in the United States. The first U.S. left-turn FYA signal was implemented in Montgomery County, Maryland in September of 2000 (Noyce, Bergh et al. 2007). The first left-turn FYA signal to in Florida was implemented in Broward County, Florida in 2002 (Noyce, Bergh et al. 2007). The authors found that FYA permissive indication is strongly recommended in the protected/permissive left-turn signal phasing (Noyce, Bergh et al. 2007).

The (MUTCD 2009) assigned a section for left-turn FYA and right-turn FYA signals. The manual explained in detail the procedures of implementing such new practice phasing of FYA. Theoretically, the four-section head FYA serves the protected permissive mode, permissive through flashing arrow mode, or protected only mode. The four-section head including FYA for left-turn or right-turn signals is considered a new standard for signalization as recommended in (MUTCD 2009); see Figures 5 and 6).

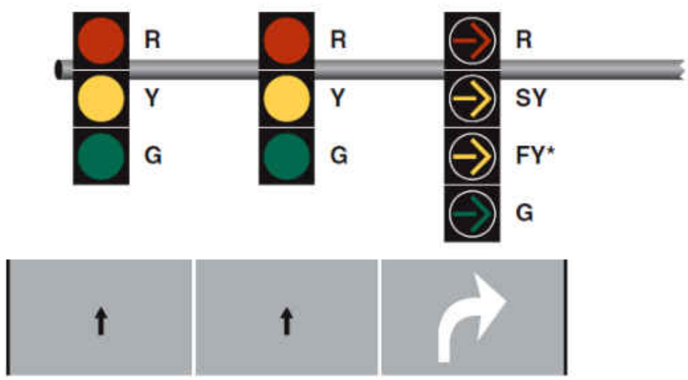


Figure 5. Four-section head signal for right approach (source: MUTCD 2009).

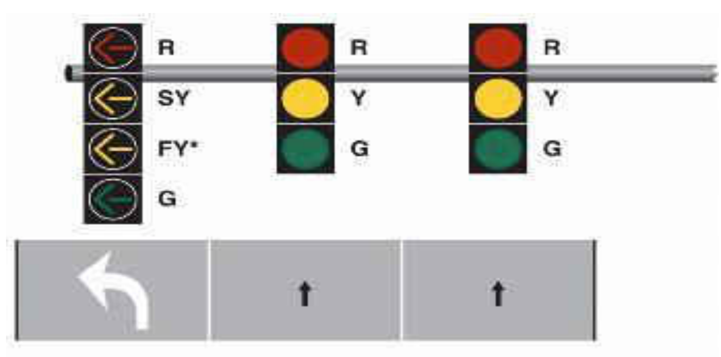


Figure 6. Four-section head signal for left-turn approach (source: MUTCD 2009).

Several requirements have been set by the MUTCD to maintain a functional flashing right-turn arrow phasing. A protected/permissive right-turn mode and a flashing right-turn yellow arrow signal should meet the following requirements:

I. The signal has the ability to display one of the following sets of signal indications:

1. "Steady right-turn RED ARROW, steady right-turn YELLOW ARROW, flashing right-turn YELLOW ARROW, and right-turn GREEN ARROW. Only one of the four indications shall be displayed at any given time," or

II. "Steady CIRCULAR RED, steady right-turn YELLOW ARROW, flashing right-turn YELLOW ARROW, and right-turn GREEN ARROW." (MUTCD 2009)

III. During a protected right-turn movement, a steady green right-turn arrow indication is displayed.

IV. A steady right-turn yellow arrow indication should be displayed following a steady green right-turn arrow signal indication.

V. During a permissive right-turn movement, a right-turn FYA signal indication shall be displayed.

VI. When the permissive right-turn movement is terminated, a steady right-turn yellow arrow shall follow the right-turn FYA signal indication and the separate right-turn signal will display a steady red indication.

VII. When a permissive right turn phase is being changed from a permissive to a protected right-turn phase, a green right-turn arrow signal indication shall be displayed immediately upon the change from the flashing right-turn yellow arrow signal indication to the steady green right-turn arrow signal indication,

VIII. "When the separate right-turn signal face is providing a message to stop and remain stopped, a steady right-turn RED ARROW signal indication shall be displayed if it is intended that right turns on red not be permissive (except when a traffic control device is in place permitting a turn on a steady RED ARROW signal indication) or a steady CIRCULAR RED signal indication shall be displayed if it is intended that right turns on red be permissive." (MUTCD 2009)

IX. The right-turn approach may have a right-turn FYA signal indication for a permissive right-turn movement while the adjacent through movement signal faces display steady circular red indications.

X. During steady mode (stop-and-go) operation, the signal section that displays the steady right-turn yellow arrow during the change interval should not be used to display the flashing right-turn yellow arrow signal indication during the permissive right-turn movement (MUTCD 2009).

Noyce, D. A., Bergh, C. R., & Chapman, J. R. (2007) completed a surrogate before-and-after analysis for the permissive left-turn FYA signal indication. They collected data for several sites with between 8 and 24 hours of videotaping. Traffic conflict and traffic operation were the main evaluated elements. The authors found "no significant change in traffic operations, or obvious driver confusion, during the initial turn on of the FYA or in periods shortly thereafter. Results supported the laboratory and driving simulator findings" (Noyce, Bergh et al. 2007).

(Qi, Yuan et al. 2012) conducted a study on protected-permissive-left turn (PPLT) operations and found that the majority of drivers comprehended the indication of FYA. They stated that most previous studies confirmed that the FYA indication performs as well as or outperforms the circular green (CG) indication in terms of driver comprehension. Moreover, the authors observed no safety issues at most studied intersections and investigated the FYA regarding safety issues at signals with the PPLT control mode. Historical crash data were collected at 17 intersections with FYA implemented. In most cases, they observed that the installation of a FYA signal indication did not worsen the traffic safety at the applied intersections. The authors concluded that PPLT FYA operations were not recommended at high demand left-turn opposing volumes.

(Pulugurtha, Agurla et al. 2011) investigated safety issues in the implementation of the FYA signal indication. They adopted the empirical Bayes (EB) method to investigate data for six intersections and found that there was no significant increase in the crash rate for intersections having left-turn FYA signals.

Hurwitz, Monsere et al. (2018) studied the implementation of the flashing yellow indication on a permissive right turn to investigate the safety and operational effectiveness of implementing FYA at exclusive right-turn lanes based on three research tasks. First, the research team developed a web-based survey to understand the Oregon driver's conception of right-turn signal alternative indications. The second task was to investigate several PPRT phasing alternatives' performance in multiple volume levels of right-turn vehicles, pedestrian movements, and impeding traffic using microsimulation analysis. The last task was to examine motorists' comprehension in response to the right-turn signal indications using a driving simulator experiment with two levels of pedestrian activity and turning bays' length.

Hurwitz, Monsere et al. (2018) used VISSIM software and an ASC/3 virtual controller to build the simulated scenarios and develop signal timing and phasing plans, using "VISSIM 7.0 with overlaps to allow the left- and right-turn flashing yellow arrows to function appropriately" (Hurwitz, Monsere et al. 2018). The objective was to examine the operational performance of several PPRT phasing alternatives under multiple volume levels. Overall, the various PPRT phasing alternatives showed little to no change in delays with an increase of right-turn volumes and impeding volume of pedestrian. The delay was significantly affected by the pedestrian volumes, but the permissive right-turn flashing yellow indication was well comprehended by Oregon drivers (Hurwitz, Monsere et al. 2018). The authors also found that drivers turning right on the FYA display significantly showed higher visual attention than turning on a permissive circular green indication: "The permissive requirement of right turns is better communicated with the flashing yellow arrow than with the circular green indication" (Hurwitz, Monsere et al. 2018).

Another study was also recently released by the University of Massachusetts, Amherst, and the University of Wisconsin, Madison to investigate the drives' comprehension of red arrows and FYAs in right-turn applications (Noyce and Knodler 2017). The authors used a survey-based evaluation and field-based evaluation of FYA at right-turn lanes. The survey evaluation, using a computer-based static evaluation, was based on existing circular green and red phase indications, the proposed FYA, and the dynamic BOS. The study proved that drivers strongly comprehended the right-turn FYA and a dynamic BOS and found that the proposed FYA message "will yield low level of confusion upon full implementation" (Noyce and Knodler 2017)

Another study of right-turn FYA was presented at the SAFER SIM 2018 conference held at the University of Central Florida. Casola (2018) conducted research on driver understanding of the FYA and dynamic *No Turn on Red* signs for right-turn applications through static evaluation and microsimulation analysis. Casola found that "Flashing and warning yellow color display increases driver's attention and yielding" (Casola (2018).

2.6 Phasing Warrants-Related Studies

2.6.1 Right-Turn Overlap Phasing Warrants-Related Studies

Right-turn phasing is considered functional at high-demand right-turn lanes (CAMUTCD, 2017; (Perez 1995). The installation of right-turn phasing requires an exclusive right-turn lane (CAMUTCD, 2017). The right-turn overlap phasing contributes to other traffic factors to improve the right-turn operation, especially at highly demanded pedestrian and traffic volume lanes (Perez 1995, FDOT 2015, CAMUTCD 2017). Few right-turn phasing warrants studies were found in the literature; most studies focused on the permissive or protected/permissive left-turn phasing.

(Perez) (1995) conducted a study of 20 signalized intersections to warrant the efficient use of the right-turn overlap phasing at an intersection. The analysis was based on the total delay reduction in vehicle per seconds the right-turn overlap phasing would cause. Perez found that the addition of right-turn phasing reduced the vehicular delay by 66 seconds in a peak hour over that reduction caused by the addition of a right-turn lane. Perez (1995) developed guidelines to determine an appropriate breakeven point in a cost/benefit analysis for the efficient implementation of right-turn overlaps phases.

2.6.2 Left-Turn Lane Phasing Warrants-Related Studies

Several studies have been conducted to warrant the left-turn approach phasing. The existing warrants were based on different research aspects. (Agent and Deen 1978) researched the left-turn phasing warrants implemented in 45 U.S. states. The numerical warrant procedures for separate left-turn phasing were mainly warranted based on the product of the left-turn peak hour volume and the opposing traffic, left-turn crashes in a 1-year period, the delay of left-turning vehicles, average speed of through traffic, or left-turn volume during a peak hour (Agent and Deen 1978).

Agent and Deen (1978) established volume warrants in the relationship between left-turn delay and traffic volume and found that the average left-turn delay varied substantially between intersections for any given volume related product (MOE). For instance, the average left-turn delay at approaches of seven intersections on a four-lane street varied from a low of 15 seconds to a high of 100 seconds for a product of left-turn and opposing 1-hour volumes of approximately 100,000. The results indicated a left-turn phase should not be implemented with an existing signal unless a delay study showed an excessive delay even with the calculated product above the specified warrant value (Agent and Deen 1978).

2.6.3 Left-Turn FYA Warrants-Related Studies

Radwan, Abou-Senna et al. (2013) developed warrants for left-turn FYA signals based on operational and safety analyses. The research was conducted at 13 intersections in Central Florida to involve a sufficient sampling of intersections. Only two intersections had FYA signals at left-turn lanes. The data were collected using several procedures such as videotaping, field observing, and historical crash data collection. A total of 150 hours of video data was recorded at the 13 intersections. Radwan, Abou-Senna et al. (2013) developed regression models to predict the amount of left-turn volume during the permissive phase. The experiment included 11 main independent variables and one quantitative dependent variable response. The system was built to determine whether a permissive phase would be feasible for the left turners during the peak hour. Then the authors built a decision support system based on a number of obtained thresholds to determine the feasibility of making permissive left turns at such a permissive left-turn phase at each approach.

Davis, Hourdos et al. (2015) developed guidelines for permissive left-turn phasing with a flashing yellow arrow based on crash analysis. A sample of 438 crashes at four different types of left-turn protection phasing was analyzed to predict the crash risk occurrence at permissive phase operations during the day. The research objective was to develop statistical models based on crash frequency to warrant permitted left-turn phasing using a flashing yellow arrow. The left-turn volume, the opposing volume, and the opposing left-turn volume were estimated based on statistical models to adjust the available turning movement volume to the appropriate days and hours. Then those adjusted hourly volumes, opposing traffic speed limits, types of left-turn phasing, and sight distance conditions of left-turning lanes were used as independent variables in statistical models to predict how the crash risk for a left-turn crash varies as the hourly volumes vary throughout the entire day.

2.7 No Turn on Red and Yield to Ped BOSs

Pedestrian activity is a critical aspect of signalized intersection operation and safety. In most states, vehicular traffic may turn right on red after a full stop, which may lead to conflict with pedestrians crossing the main street unless a *No Turn on Red* sign is applied (Herman 2002). Therefore, a pedestrian crash caused by vehicular traffic was found significant during right turn on red (Preusser, Leaf et al. 1982). The driver most likely would be looking left to find a gap in traffic and turn right without yielding to pedestrians coming from the right (Herman 2002). Other research has found that a right turn on red does not have a significant impact on pedestrian safety (McGee 1977, AASHTO 1979).

Motorists turning right on green must yield to pedestrians crossing on a walk signal for the side street (Herman 2002). Therefore, *Yield to Pedestrians* or Pedestrians Watch for Turning

Vehicle signs are commonly used to mitigate pedestrians' risks related to turning traffic (Zegeer, Opiela et al. 1982). Figures 7 and 8 illustrate an example of *No Turn on Red* and *Yield to Pedestrians* signs.

Figure 7. Standard *No Turn on Red* Sign (MUTCD 2009).

Figure 8. Standard *Yield to Pedestrians* Sign (MUTCD 2009)

Crashes involving right-turning vehicles on red with crossing traffic or turning traffic are more likely at signalized intersections (Alluri, Haleem et al. 2013). Alluri, Haleem et al. (2013)stated that a number of drivers turning right on red do not make a full stop and might block the crosswalk to watch for a gap in the through traffic. Therefore, the implementation of a *No Turn on Red* sign or an electronic BOS is might be crucial in mitigating this attribute (Harkey and Zegeer 2004). Figure 9 illustrates examples of electronic *No Turn on Red* and *Yield to Pedestrians* BOSs.

The (MUTCD 2009) has listed six cases that require an implementation of a *No Turn on Red* sign. Three of these cases are tied to pedestrian's activity; significant pedestrian's conflict resulted from right-turn on red and an exclusive pedestrian's phase, and a significant number of pedestrians are elderly, children, or handicapped.

Figure 9. Blank out signs.

A pedestrian safety study at right turn on red intersections conducted by Zegeer, Cynecki et al. (1986) found that almost 21% of drivers violated *No Turn on Red* signs. Additionally, they found 23% among the violating drivers had led to vehicle-pedestrians conflict. They found that illuminated *No Turn on Red* signs, *No Turn on Red* signs with a red ball underneath, and offset stop bars at intersections where right turn on red was allowed significantly improved pedestrian safety during right-turn-on-red maneuvers (Zegeer, Cynecki et al. 1986). They stated, “The illuminated *No Turn on Red* sign was found to be a slight improvement compared to the standard *No Turn on Red* sign, in terms of fewer violations” (Zegeer, Cynecki et al. 1986, Herman 2002).

The new variable message signs have been used in Orlando, Florida to improve pedestrians’ safety conflicting with right-turning vehicles (Herman 2002). The variable message signs essentially direct motorists in right-turn lanes by displaying the message, *No Turn on Red* during the red phase and *Yield to Peds* during the green phase (Herman 2002).

Herman (2002) did a treatment and control design study to investigate the impact of the current variable massage system on the behavior of road users. Six treatment and control intersections were used in the investigation in downtown Orlando, Florida. The study found that the variable message signs significantly lowered the percentage of *right-turning vehicles* on red, compared to the control sites. In addition, he observed that motorists were more likely to yield to a group than to individual pedestrians at the treatment sites but not at the control sites.

Casola (2018) studied the driver comprehension of right-turn signs during permissive right-turn phases through static evaluation and microsimulation analysis. The traffic devices involved the FYA, the dynamic BOS *No Turn on Red*, and the existing circular green indication. The results showed "a strong similarity between the existing circular red and R10-11 sign and the proposed dynamic no turn on red sign" (Casola 2018).

2.8 Significant Parameters Affecting Right-Turn Operation

Several studies have offered analytical models, simulation, or statistical analysis using field data to quantify the significant factors leading to impeding the right-turn movement operation. Gluck, Levinson et al. (1999) developed simulation analysis to estimate the delay caused at right-turn lanes. The research team found that the delay by right-turning traffic increased exponentially as the volume in the driveway increased. In addition, the increase in speed difference in through traffic and driveway entrance was found to increase the delay (Gluck, Levinson et al. 1999). McCoy, Ataullah et al. (1993) simulated uncontrolled right-turn approaches with shared and exclusive lanes using NETSIM software. The authors aimed to develop the delay equation for an uncontrolled approach with the existence or absence of right-turn lanes for two-lane and four-lane roads. The delay function showed that the delay for right-turn vehicles was affected significantly by approach speed of the roadway, approach volumes, volumes of right turning vehicles and the interactive term expressed as the product of volumes of right turning vehicles and presence/absence of right turn lane.

The highway capacity manual listed seven significant parameters associated with the influence of RTOR movements:

- Traffic demand in vehicle per hour (vph);
- Approach lane configuration;
- Sight distance at the intersection approach;
- Degree of saturation at certain approaches;
- Arrival patterns;
- Left-turn signal phasing on conflicting street; and
- Conflict with pedestrians and bicycle traffic.

The seven factors lead to comprehension of how well the right-turning vehicles on red movement were treated. Generally, it can be concluded that the seven factors determine the type of right-turn treatment in signalized and non-signalized intersections.

Tarko (2001) developed a mathematical equation based on the modified HCM equations to calculate the maximum volume for the permissive RTOR. The equation was estimated based on two impeding factors and other contributing factors as listed below:

- Impeding vehicular flow (vph);
- Expected signal cycle;
- Critical gap for right turns (6.9 s);
- Follow-up time (3.3 s); and
- Phase for the impeding flow.

Tarko concluded, “The impeding flow is the volume of through vehicles that use the rightmost lane on the approach located to the left of the right turners’ approach” (Tarko 2001).

2.9 Literature Conclusions

The literature has intensively reviewed several statistical and analytical studies for right-turn treatment guidelines and left-turn signal warrants. The reviewed warrants were mainly developed based on operational and safety aspects. The literature review generated an overview study on the right-turn signal phasing. The literature has mainly focused on the signal phasing warrants for the right-turn phases at signalized intersections. I reviewed most states' manuals to look at their right-turn signal guidelines. In addition, major manuals such the MUTCD and FHWA were reviewed to help understand the different aspects of right-turn signal phasing practices. The MUTCD manual was the main reference followed to define the FYA signal phase for the left- and right-turn movements.

Studies have stated that the implementation of FYA had no effect on intersection or approach safety. Furthermore, previous FYA studies found no significant change in traffic operation associated with the implementation of FYA signal phasing. Finally, the studies found that the FYA phasing indication was clearly comprehended by the roadway users and did not show significant confusion for the implementation of the new practice phasing.

Also, few studies were found to study the right-turn phasing warrants guidelines. Most right-turn warrants were developed to warrant the construction of right-turn lanes on a rural highway or to dedicate an exclusive right-turn lane at signalized intersections. Right-turn overlap phasing is considered the major phasing treatment at right-turn approaches. So far, the literature review showed no right-turn FYA signal phases guidelines in place with a focus on the left-turn FYA signal phasing system. There is a crucial need to conduct research for permissive right-turn FYA signal phases and to develop operational warrants for the efficient implementation of the new right-turn FYA signal phasing practice.

CHAPTER 3: METHODOLOGY

3.1 Research Plan

With this research, I aimed to develop warrants that led to efficient implementation of a permissive protected right-turn PPRT FYA signal at an exclusive right-turn lane. I investigated three permissive right-turn FYA signal phases in different traffic approaches, signal timing plans, and pedestrian circumstances. They involve two right-turn on adjacent lanes through red phases and a right turn on adjacent lanes through green phase. The first right-turn-on-red phase, right turn on impeding through (RTOIT), is impeded by the cross street through traffic and pedestrians crossing the main street. The second right-turn-on-red phase, right turn on impeding left (RTOIL), is impeded only by the opposing left-turn traffic. The right-turn on green phase and right-turn on adjacent through (RTOAT), occurred during the adjacent through lane green phase and is impeded only by pedestrian crossing the side street (see Figure 10 and Table 1).

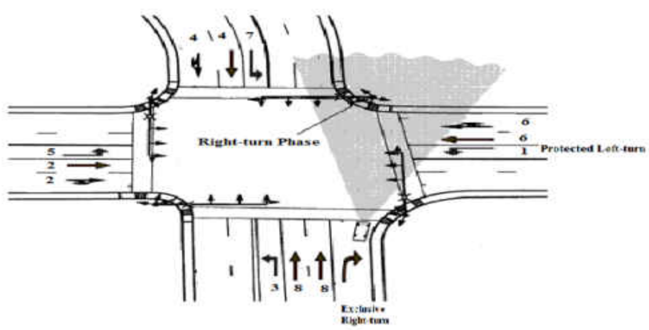
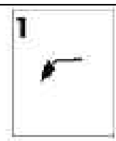
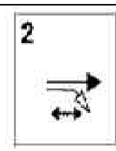
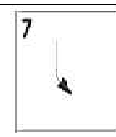
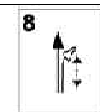


Figure 10. Signalized intersection phasing coordination (FHWA 2015).

Every permissive right-turn phase was investigated in a separate systematical stochastic analysis using a set of impeding traffic flows, impeding phase intervals, and/or impeding pedestrian volumes. The maximum right-turn throughput (MRTT) vph was the main measurement used to assess the efficient implementation of a permissive right-turn FYA phase. Otherwise, a protected red arrow phase complemented with BOS of No Turn on Red was recommended if the permissive phase were not feasible.

Table 1: Right-Turn Movements Coordination Types

Coordination	Overlap	**RTOIT**	**RTOIL**	**RTOAT**
Moving Approaches				
Right-Turn types	Protected Green Arrow	Right Turn on Impeding Through	Right Turn on Impeding Left	Right Turn on Adjacent Through

I extensively researched the measures of effectiveness and thresholds that properly assess a permissive right-turn phase. I deduced the number of sneakers' methodology to appropriately predict the efficiency attribute of a permissive right-turn FYA signal phase. A *sneaker* is defined as a vehicle that waits before the stop line of an intersection and departs after the green time (Wu 2011). The *Highway Capacity Manual* (HCM (2010) defined sneaker as a number of left turns per cycle that departed at the end of a permissive phase. It is an accepted practice in the traffic field to assume two sneakers during permissive phases (Martin, Perrin et al. 1998). Wu (2011) proposed a model to estimate the capacity of a shared lane and adopted two sneakers per cycle according to the approximation formulas (Harders 1968). The model was applied to permissive shared left-turn and right-turn lanes.

Consequently, the research methodology considered a permissive right-turn phase with an average of two throughputs per cycle (average MRTT per cycle) is not warranted. Precisely, a permissive right-turn FYA signal phase is not feasible if only two sneakers per cycle might be discharged on an impeding phase. The sneakers find no gaps during the impeding green interval and only use the amber and/or clearance intervals to depart. Thus, the average MRTT per cycle measurement results obtained from the DOEs' MOE (MRTT vph) were categorized into three attributes based on an efficiency score. Nonefficient (NE) category highlights all MRTT vph results that have an average MRTT per cycle less or equal to two right-turn throughputs. Low-efficient (LE) category highlights all MRTT vph results with an average MRTT ranging from 2.1 to 2.9 throughputs per cycle. Lastly, The Efficient (E) category highlights all MRTT vph results that have an average MRTT per cycle of three throughputs or more per cycle.

3.2 Design of the Experiments DOEs

The right-turn FYA signal phases warrants involve three DOEs listed in Chapters 6, 7, and 8. The DOEs investigated three permissive right-turn phases under a set of significant parameters: RTOIT, RTOIL, and RTOAT. The MRTT vph is the measure of effectiveness (MOE) in the three DOEs. The permissive right-turn FYA phases were investigated in a stochastic analysis study to warrant an efficient right-turn FYA signal. The past studies stated that right-turn movements are significantly affected by the degree of saturation at certain approaches, arrival patterns, left-turn signal phasing on conflicting streets, and conflict with pedestrians and bicycles (McCoy, Ataullah et al. 1993, HCM 2010). Tarko (2001) found a significant impact of the impeding traffic phase and the signal cycle on the right-turn on red maximum throughputs. The DOEs were developed using a set of parametric variables including an impeding flow, an impeding green interval, cycle length, and pedestrian volume.

CHAPTER 4: DATA COLLECTION

4.1 Overview

Right-turn phasing is widely implemented in the United States and exists at high-demand right-turn lanes and three-legged signalized intersections. Previous studies found that right-turn phasing with overlap enhances the right-turn traffic performance and provides a protected phase simultaneously with the cross-street left-turn movement (Perez 1995). The right-turn FYA signal is the latest practice phasing in the United States. There are only a few signalized intersections implementing the new practice phasing. The five-section head, right-turn phasing, the dog house signal head, is a protected permissive right-turn phasing system that allows three permissive right-turn phases: on red, on a circular green, and on a protected green arrow (overlap phase). The right-turn FYA works on the same concepts allowing three permissive phases and a protected green arrow phase. The author and research team of the Center for Advanced Transportation Systems Simulation at University of Central Florida (CATSS) decreed that the right-turn, five-section head phasing signal is a PPRT phase, which supports the same protected permissive modes on the right-turn FYA signal.

To develop right-turn FYA signal warrants, single exclusive PPRT right-turn phasing systems have to be deeply investigated under several traffic and signal timing conditions. I searched vast right-turn signal locations and proposed several signalized intersections that implement a single exclusive PPRT phasing signal in Central Florida. In addition, the Orange County Department of Transportation, represented by Mr. Hazem El-Assar, has provided significant effort and cooperation to provide necessary information and data.

4.2 Candidate Locations

The proposed PPRT phasing signal locations are at the following:

1. Alafaya Tr. at Lake Underhill Rd. intersection (five-section head signal at four-legged intersection);
2. Lake Underhill at Waterford Chase (five-section head signal at three-legged intersection);
3. Woodbury at Waterford Pkwy (five-section head signal at three-legged intersection).

I selected the listed locations based on several factors such as traffic demand, geometric conditions, and data availability. The research team agreed to select Alafaya Tr. at Lake Underhill Rd intersection to be the main signalized intersection in this study after a heavy traffic and geometry qualification overview (see Figure 11).

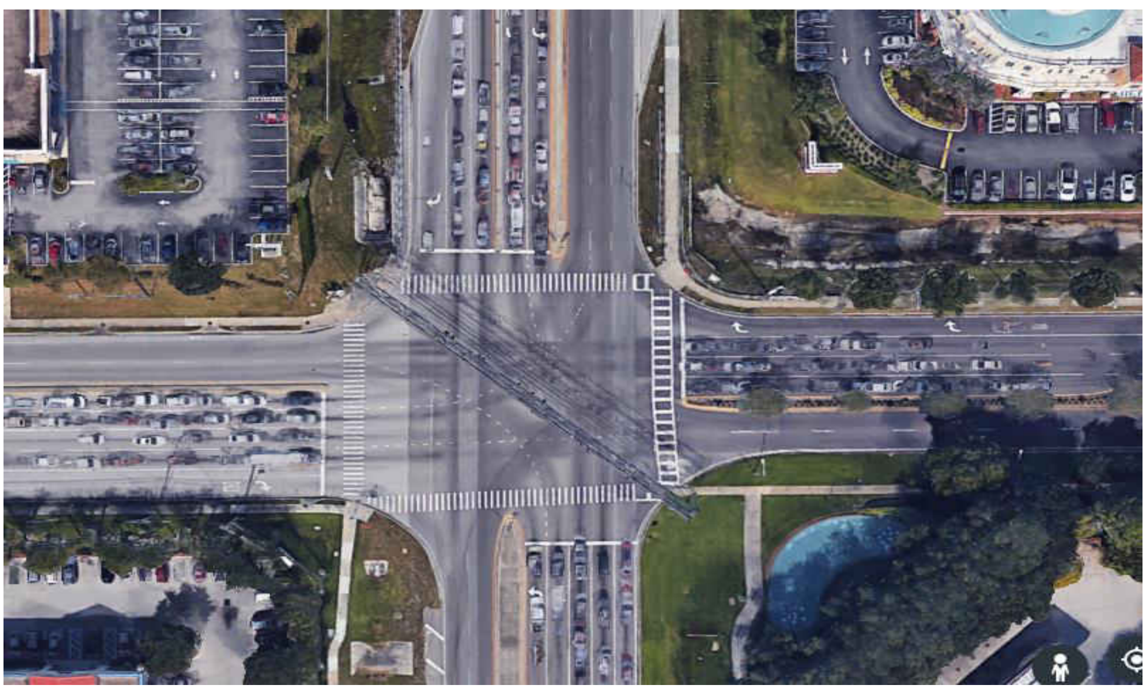


Figure 11. Alafaya Tr. At Lake Underhill Rd. intersection Layout (Source: Google Earth 2017).

4.3 Intersection Geometry

The studied intersection, Alafaya Tr. at Lake Underhill Rd. intersection, is located on two major urban arteries that serve heavy traffic volumes along several signalized intersections in East Orland. The southbound direction has double through lanes, an exclusive right-turn lane, and exclusive double left-turn lanes. The northbound direction has double through lanes, one shared through/right lane, and double exclusive left-turn lanes. Lake Underhill Rd. serves double through lanes, an exclusive right-turn lane, and exclusive double left-turn lanes in the eastbound direction and an exclusive left-turn lane in the westbound direction. The westbound approach has double through lanes, an exclusive right-turn lane, and an exclusive left-turn lane. Bing satellite images present in VISSIM were used to measure all the intersection lanes' lengths and widths.

4.4 Volumes and Vehicle Composition

The studied intersection is considered a high-demand traffic intersection and saturated through all approaches, especially at peak hours. Vehicle composition was coded as 98% passenger cars and 2% heavy vehicles, based on the data obtained from Orange County, Department of Transportation in Central Florida. The field volumes used in the VISSIM for calibration purposes were provided in the form of a Synchro file and turning movement counts (TMC) by the Orange County, Department of Transportation in Central Florida on February 11, 2018. The PM peak period volume data were adopted in this study. See Figure (12). The data collection effort included:

- Turning movement counts TMCs at three times of day listed in Table 3;
- Intersection inventories and existing timing data;
- Local controller backup signal timing;
- Vehicle speed profiles; and

- Pedestrian volume.

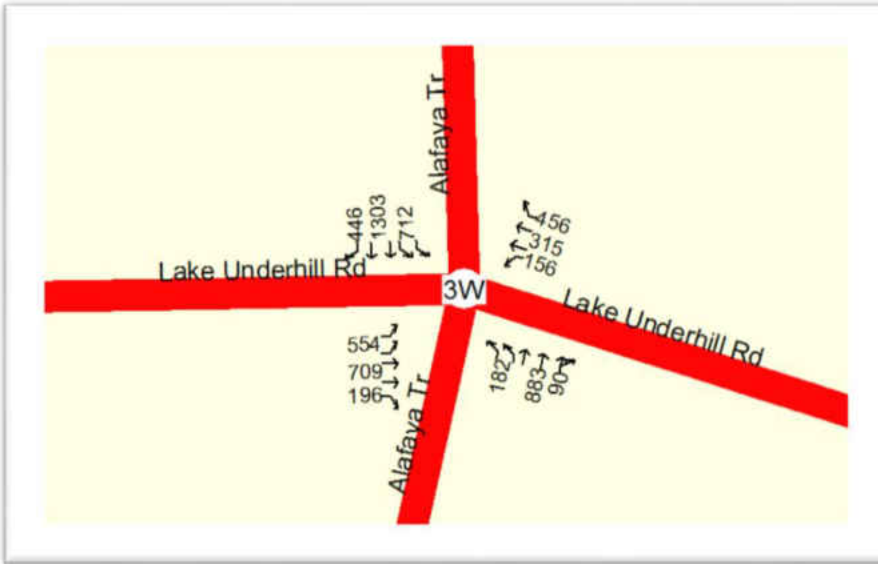


Figure 12. Synchro input volumes of the studied signalized intersection.

4.5 Signal Timing

The signal timing plan for this intersection was obtained from the Synchro reports provided by OC in central Florida as illustrated in Table 2 and Figure 12. This runs as an 8-phase intersection, with four protected left-turn phases and a protected/permissive right-turn phase in the eastbound approach. The studied PPRT signal (westbound to northbound movement) displayed three signal indications. A protected green arrow indication appeared during the non-conflicting southbound left turn phase while the U-turn was prohibited. A green solid ball was displayed during the adjacent westbound through movement. Red solid balls were displayed during the northbound through and the eastbound left turn movements. The intersection signal timing was optimized perfectly to tolerate high demanded through and of left-turn movement volumes. The intersection's ring barrier controller was coordinated with cycle lengths ranging from 150–170 seconds, depending on the time of day. Table 2 shows the evening peak hour signal timing system. The current intersection was systematically phased with an adaptive signal timing system. The collected signal timing was installed on the controller as a backup signal timing sheet.

Table 2: *Signal Timing Sheet for Alafaya at Lake Underhill Intersection (PM Peak)*

Signal Number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
SG Name	**SBL**	**NBT**	**WBL**	**EBT**	**NBL**	**SBT**	**EBL**	**WBT**	**RT**
Minimum Green	5	15	5	5	5	15	5	5	138
Veh Extension	2	2	2	2	2	2	2	2	2
Max Green	41	46	17	39	13	74	32	24	138
Yellow	4.8	4.8	4	4.8	4.8	4.8	4.8	4	4
Clearance	2	2	2.3	2	2	2	2	2.3	2.3
	Pedestrians phases								
Pedestrians Phase	102			104		106		108	
Walking	7			5		7		5	
Pedestrians clear (FDW)	36			20		31		20	

Table 3: Turning Movement Counts in Three Time of Day Plans for Alafaya at the Lake Underhill Intersection

	Alafaya Tl Southbound				**Lake Underhill Road Westbound**				**Alafaya Tl Northbound**				**Lake Underhill Road Eastbound**				
Start Time	Left	Thru	Right	App. Total	Left	Thru	Right	App. Total	Left	Thru	Right	App. Total	Left	Thru	Right	App. Total	Int. Total
7:45	**77**	**143**	70	**290**	37	**193**	214	**444**	**58**	335	15	408	64	**52**	13	129	1271
8:00	60	108	48	216	**47**	157	**216**	420	58	332	8	398	71	50	15	136	1170
8:15	59	113	**72**	244	40	157	184	381	42	388	10	440	73	44	13	130	1195
8:30	69	143	56	268	37	130	215	382	48	**393**	**19**	**460**	**96**	48	**19**	**163**	**1273**
Total Volume	265	507	246	1018	161	637	829	1627	206	1448	52	1706	304	194	60	558	4909
% App. Total	26	49.8	24.2		9.9	39.2	51		12.1	84.9	3		54.5	34.8	10.8		
PHF	0.86	0.886	0.85	0.878	0.86	0.825	0.959	0.916	0.888	0.921	0.68	0.927	0.792	0.933	0.789	0.856	0.964
12:00	116	201	89	406	36	**93**	122	**251**	36	219	22	277	**158**	98	38	294	1228
12:15	122	193	108	423	**42**	75	122	239	36	**248**	21	**305**	131	107	25	263	1230
12:30	**135**	**244**	110	**489**	36	75	**123**	234	**44**	225	**30**	299	140	107	33	280	1302
12:45	129	212	**145**	486	42	77	122	241	33	227	23	283	150	**136**	**41**	**327**	**1337**
Total Volume	502	850	452	1804	156	320	489	965	149	919	96	1164	579	448	137	1164	5097
% App. Total	27.8	47.1	25.1		16.2	33.2	50.7		12.8	79	8.2		49.7	38.5	11.8		
PHF	0.93	0.871	0.78	0.922	0.93	0.86	0.994	0.961	0.847	0.926	0.8	0.954	0.916	0.824	0.835	0.89	0.953
16:15	169	304	**140**	613	**43**	72	109	224	**64**	184	18	266	129	164	39	332	1435
16:30	137	308	116	561	36	64	112	212	31	198	**30**	259	140	157	51	348	1380
16:45	**203**	**356**	99	**658**	35	83	116	234	45	**251**	18	314	138	185	51	374	1580
17:00	203	335	91	629	42	**96**	**119**	**257**	42	250	24	**316**	**147**	**203**	**55**	**405**	**1607**
Total Volume	712	1303	446	2461	156	315	456	927	182	883	90	1155	554	709	196	1459	6002
% App. Total	28.9	52.9	18.1		16.8	34	49.2		15.8	76.5	7.8		38	48.6	13.4		
PHF	0.877	0.915	0.8	0.935	0.91	0.82	0.958	0.902	0.711	0.879	0.75	0.914	0.942	0.873	0.891	0.901	0.934

CHAPTER 5: THE MICROSIMULATION AND DRIVING BEHAVIOR

5.1 Microsimulation Overview

The microsimulation tool is an analytical method to perform appropriate traffic analysis. It can simulate traffic segments and nodes such as network geometry, traffic features, signal systems, and pedestrian operations. Much research has been conducted using microsimulation software such as VISSIM, CORISM, AMISUN, SIMTRAFFIC, PARAMICS, and INTEGRATION (Almoshaogeh, Radwan et al. 2018). The microsimulation application varies in the point view of the reliability and the applicability of imitating the new designs, ability of simulation signal control practices and/or import signal plans from other tools, and the capability of the running of the simulation for different replications and random seeds easily and other factors (El Esawey and Sayed 2013). I used VISSIM Version 10.02 to simulate the different right-turn phasing patterns. VISSIM software is a stochastic microsimulation tool developed by the PTV group. It can measure vast traffic measurements as well as simulate movement, approach, link, route, area, and other pedestrian possibilities (Siromaskul and Speth 2008).

5.2 Simulation Software

Initially, the studied signalized intersection model was developed using Synchro 9.0, a microsimulation and signal timings optimization software. Thereafter, the Synchro simulation model was exported to a VISSIM version 10.02 file. I then modified the file to fit the studied intersection and accurately replicate the PPRT phasing practice at the westbound approach. VISSIM with overlaps was used to allow the implementation of PPRT phasing at the westbound approach. Figure 13 illustrates the Alafaya Tr. at Lake Underhill Rd. intersection network simulated in VISSIM. Figure 14 illustrates four right-turn phases coded using the overlap command provided in VISSIM. The right-turn phases are illustrated in Figure 14a–d in sequence for the overlap, RTOAT, RTOIT, and RTOIL phases.

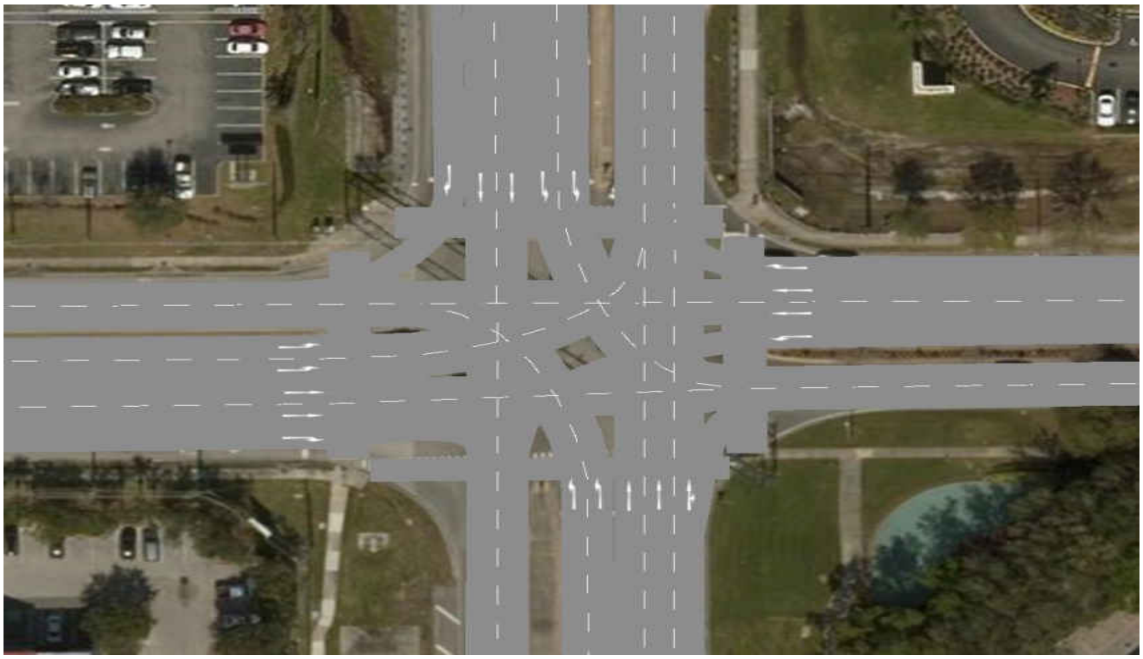
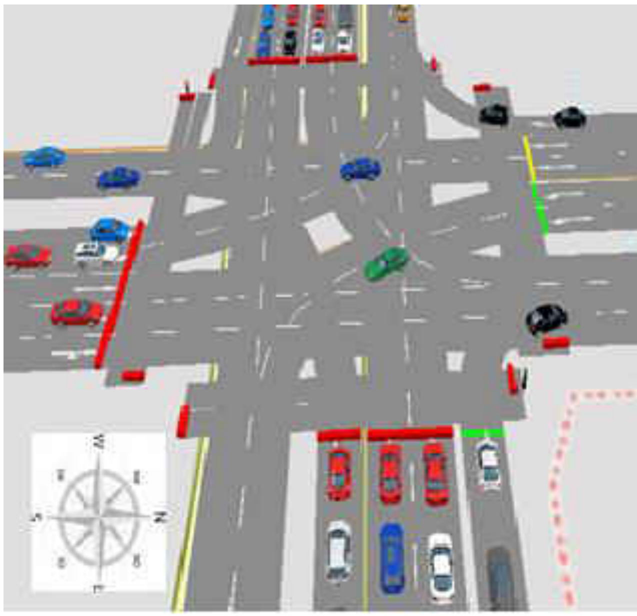
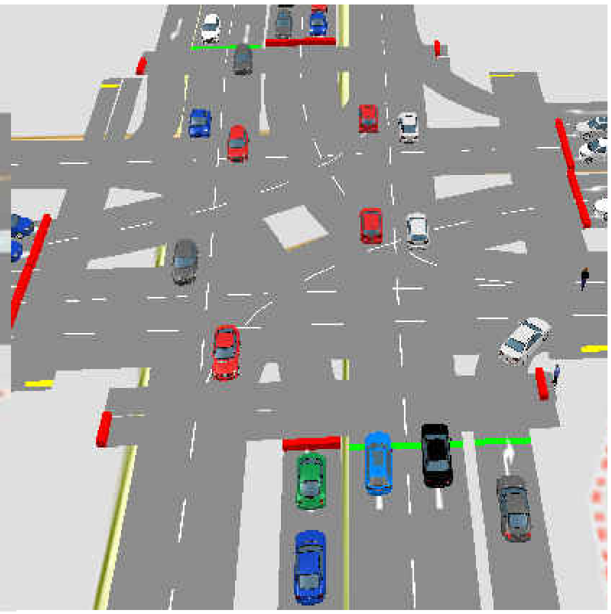


Figure 13. Alafaya Trail at Lake Underhill VISSIM Network.

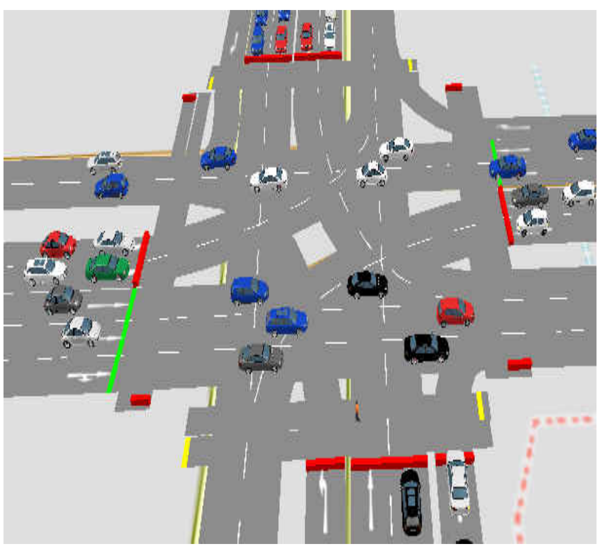
5.3 Driver Behavior Parameters

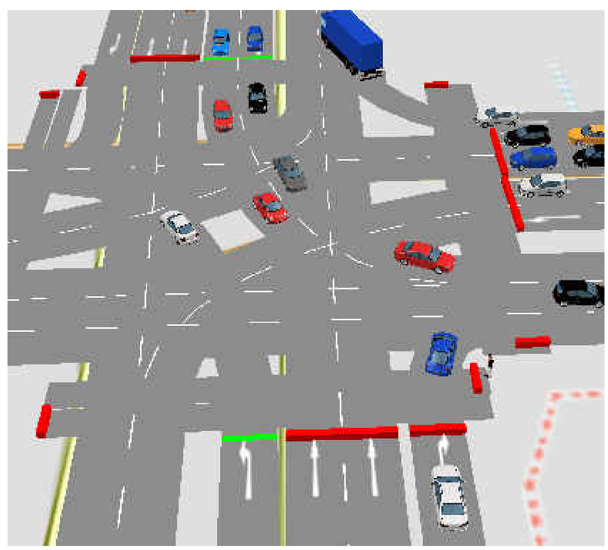
The stochastic microsimulation was built based on several parameters such as the number of replications, simulation period, seeding number, and driver behavior values. The VISSIM software was designed to run according to a car-following model presented by Wiedemann and Fellendorf (Fellendorf and Vortisch 2001; Wiedemann & Reiter, 1991(Wiedemann and Reiter 1991, Fellendorf and Vortisch 2001). The Wiedemann model involves 10 driver behavior parameters labeled with the CC prefix. Each of the parameters controls an aspect of the car following model (Woody 2006). Table 10 illustrates the Wiedemann parameters with a brief description and default value for each CC parameter.





(a) (b)





(c) (d)

Figure 14. Simulation network and overlap phasing illustration.

To achieve an accurate model that replicates the existing condition, I had to identify a proper set of driver parameters. Hurwitz, Monsere et al. (2018) used default driving behaviors within VISSIM to study the performance of protected permissive right-turn flashing yellow arrows in Oregon. Based on that, the model was run using the default driver behavior parameters set provided in VISSIM 10.02 in 10 replication runs. The default parameters set obtained an accurate model that matched the model outputs and the field condition at less than 3% error. Moreover, the outputs of the VISSIM model implementing the default driving behavior parameters were a 97% replication of the field condition for all the studied signalized intersection approach movements. The studied right-turn phase exclusive lane with its impeding through and left movements listed in the DOEs were parts of the study of the driving behavior parameters. Previous studies stated that the calibration wouldn't be required if the error percentage for the initial evaluation using the default values were less than 5% (Toledo, Koutsopoulos et al. 2003, Tarko, Inerowicz et al. 2008) As a result, the calibration and validation of the VISSIM model were not needed in this study as the values of the default driver behavior parameters set proved an accurate VISSIM model output in comparison with the field data.

During the driving behavior study process, the VISSIM model was run based on actuated ring barrier control that exactly duplicated the existing condition. Traffic volume demands were compared with the traffic volume throughputs at the studied westbound exclusive right-turn lane with all other approaches for the adopted signalized intersection. This way, I assessed the accuracy of the VISSIM model that runs based on the default driving behavior values. The default driving behavior parameters set was reliable, and I took further steps to achieve the research objective by completing the proposed three DOEs.

Table 4*: Wiedmann 99 Parameters (VISSIM Manual, 2017)*

Category	VISSIM Code	Description	Default Value
Thresholds for Dx	CC0	**Standstill distance:** Desired distance between lead and following vehicle at v = 0 mph	4.92 ft
	CC1	**Headway Time:** Desired time in seconds between lead and following vehicle	0.90 sec
	CC2	**Following Variation:** Additional distance over safety distance that a vehicle requires	13.12 ft
	CC3	**Threshold for Entering Following State:** Time in seconds before a vehicle starts to decelerate to reach safety distance (negative)	-8.00 sec
Thresholds for Dv	CC4	**Negative "Following" Threshold:** Specifies variation in speed between lead and following vehicle	0.35 ft/s
	CC5	**Positive "Following" Threshold:** Specifies variation in speed between lead and following vehicle	0.35 ft/s
	CC6	**Speed Dependency of Oscillation:** Influence of distance on speed oscillation	11.44
Acceleration Rates	CC7	**Oscillation Acceleration:** Acceleration during the oscillation process	0.82 ft/s^2
	CC8	**Standstill Acceleration:** Desired acceleration starting from standstill	11.48 ft/s^2
	CC9	**Acceleration at 50 mph:** Desired acceleration at 50 mph	4.92 ft/s^2

CHAPTER 6: RIGHT TURN ON IMPEDING THROUGH RTOIT WARRANT

6.1 Understanding RTOIT

The RTOIT is a permissive right-turn movement impeded by the cross-street through traffic and pedestrians crossing the main street parallel to the impeding vehicular traffic. The impeding volume was assumed uniformly distributed at the impeding through lanes. This step was considered to ensure that the impeding rightmost lane volume acquired the listed volume per lane in the DOE. VISSIM software cannot be used to allocate volume per lane for an exact lane but for the whole movement volume. According to Tarko (2001), “a long right-turn bay for right turners removes them effectively from the rightmost through lane, thus the through traffic is uniformly distributed across the continuous lanes” (p.8). Otherwise, Tarko (2001) stated that “The assumption of uniform traffic distribution is valid if the through traffic is strong enough to use the rightmost lane despite of the presence of right-turning vehicles” (p.9). Therefore, to maintain uniform traffic volume distribution in the impeding through traffic lanes, through traffic was designed with an exclusive long right-turn bay.

6.2 RTOIT Measures of Effectiveness

The maximum right-turn volume was the only measure of effectiveness MOE used in the DOE to warrant the efficiency attribute of the permissive RTOIT phase. The MRTT vph was used in many studies to predict the right-turn capacity in a permissive right-turn phase (Tarko 2001, Creasey, Stamatiadis et al. 2011). I used it to assess the efficient implementation of a permissive RTOIT FYA signal phase. To measure the MRTT during a permissive right-turn phase properly, westbound right-turn lane input volume was ensured to be at least 1.2 greater than the right-turn throughput volume. Correctly, the studied exclusive right-turn throughputs were measured for all scenarios before collecting RTOIT MRTT results to ensure continuous right-turn traffic demand during all PPRT phases.

6.3 RTOIT Experiment Procedures

Stochastic analysis was conducted based on a validated network in VISSIM to investigate the efficient use of a right-turn FYA signal phase during the impeding through phase. The default driving parameter's values were held constant through the whole experiment. Procedures were undertaken for the RTOIT modeling development to appropriately warrant an efficient RTOIT FYA signal phase and develop functional guidelines based on microsimulation analysis. It was based on a certain site geometry design and listed DOE input data (traffic vehicle features and signal timing parameters). These steps are described in detail in the following sections.

6.3.1 Intersection Geometry

The experiment was mainly designed based on the studied intersection, Alafaya Tr. at Lake Underhill Rd. The southbound direction has double through lanes, an exclusive right-turn lane, and exclusive double left-turn lanes. The NB approach geometry was slightly modified to fulfill the uniformity of the impeding traffic distribution. It was designed with three through lanes and an exclusive right-turn lane instead of two through lanes and one shared through/right lane. The westbound and eastbound approaches were designed with double through lanes, an exclusive right-turn lane, and exclusive double left-turn lanes in the eastbound approach, and an exclusive left-turn lane in the westbound direction. The westbound dedicated right-turn lane was designed to allow the implementation of an exclusive PPRT phasing signal. Bing satellite images present in

VISSIM allowed me to measure the intersection's all lane lengths and widths including the pedestrian crosswalks. Figure 15 illustrates the studied signalized intersection layout developed using the VISSIM vision 10.02 package.

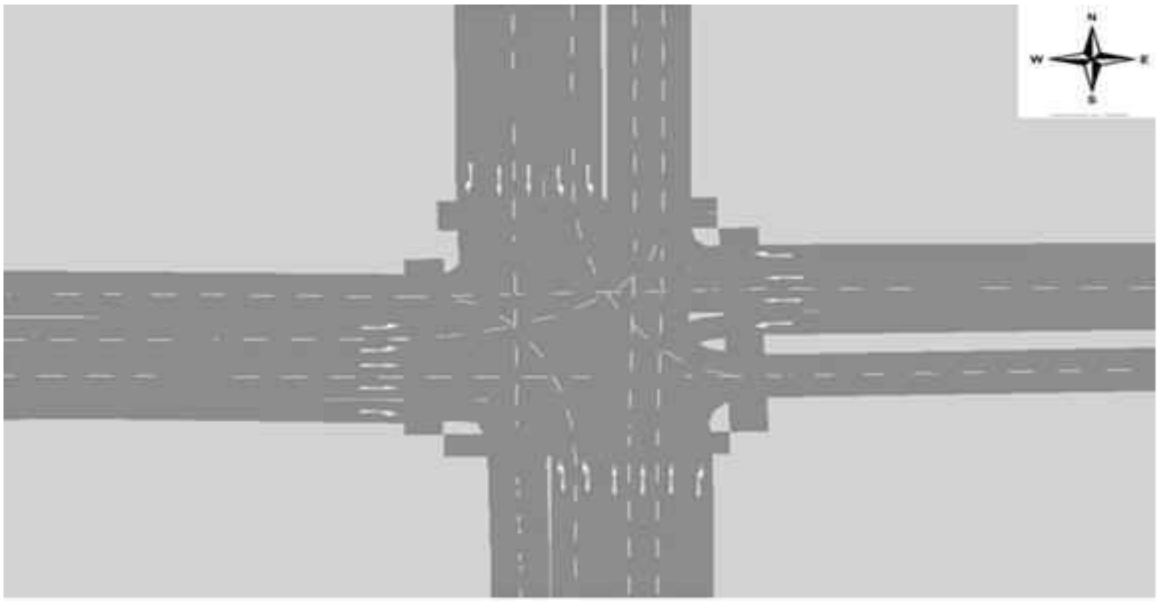


Figure 15. RTOIT intersection geometry design.

6.3.2 DOE Significant Parameters Considered

The RTOIT FYA phase DOE was designed to measure the MRTT vph in four parametric factors and to assess the efficient implementation of a permissive FYA signal phase during the RTOIT. Those listed factors were found to have a significant impact on the RTOIT capacity (Tarko 2001, HCM 2010, Creasey, Stamatiadis et al. 2011). The four significant factors are listed below:

- Impeding vehicular flow at the rightmost lane (vph);
- Impeding pedestrian volume (pph)
- Expected signal cycle (s); and
- Impeding green interval (IGI) (s).

The impeding vehicular volume was listed in a set of incremental volume levels for each IGI group in the DOE. The impeding through flows to capacity ratios for the listed incremental impeding volumes were designed to range from almost 0.70 to 1.1. The impeding flow to capacity $\frac{V}{C}$ ratio is defined in the following;

Where

V = listed hourly impeding volume for the rightmost lane (vph);

C = Impeding lane group capacity.

An impeding lane group capacity was estimated based on Equation 1. The lost time was considered 4 seconds as listed in the HCM (2010).

$$Ci = Si \times (gi/c) \quad (1)$$

Where

Ci = Impeding lane group capacity for the rightmost lane;

S= Saturation flow rate for the rightmost lane (about 1800 vph/ln);

gi/c = the effective impeding green interval to cycle length ratio for the rightmost lane;

C = Design cycle length (s).

6.3.3Signal Timing

The RTOIT FYA design of the experiment was developed through hypothetical nine signal timing plans. Each signal timing plan listed in the RTOIT DOE was optimized on an impeding northbound design green interval, a design cycle length, and impeding northbound vehicular volume. All signal timing plans run as an 8-phase intersection, with four protected left-turn phases, and a protected/permissive right-turn phase at the westbound approach. The studied PPRT phase (westbound to northbound movement) was designed to allow a functioning protected green arrow and permissive FYA indications in VISSIM. The protected green arrow was displayed during the non-conflicting southbound left turn phase while the U-turn was prohibited. The FYA indications were displayed during the adjacent westbound through, the northbound impeding through, and the eastbound opposing left turn movements. The nine signal timings were optimized perfectly as a pretimed control system in three cycle lengths for three green to cycle length (G/C) plans. The pedestrian phases were designed as a concurrent pedestrian phase that allows the pedestrian to walk parallel with the vehicle traffic receiving a green indication at the same time. Specifically, the impeding pedestrian phase was optimized to receive the walking phase display immediately as the northbound through lanes received the green indication. Synchro version 9.0 software was used to optimize the signal timing plans proposed in the DOEs. Pretimed control was adopted in this research with fixed green phases to fulfill the DOE's signal timing plans.

6.3.4 RTOIT VISSIM Coding Procedures

The Synchro signal timing plans were exported to VISSIM version 10.02 software. to replicate most of the proposed intersection geometry and accurately allow the implementation of PPRT FYA phasing practice at the westbound approach. Overlaps coding function provided in VISSIM was used to implement the protected right-turn phase and the three permissive phasing schemes. The right-turn phasing code consisted of four cases for right-turn movements: overlap, RTOIT, RTOIL, and RTOAT. Hurwitz, Monsere et al. (2018) used VISSIM with overlaps to properly function the PPRT FYA. The right-turn throughputs were collected at a second by second time basis for one hour to properly collect the MRTT vph results during the permissive RTOIT. Precisely, MRTT vph results were obtained by accumulating all right-turn throughputs that occurred simultaneously with the impeding through during the northbound phase. The signal display outputs provided by VISSIM were used to determine the RTOIT phases for all cycles. Finally, I used Excel spreadsheets to count the MRTT vph for all scenarios listed in the DOE.

6.3.5Right-Turn on Impeding through RTOIT DOE

The RTOIT MOE was obtained for various impeding vehicular flow and impeding pedestrian volumes at several signal timing plans to assess the efficiency of a permissive RTOIT FYA phase. The experimental design resulted in more than 100 scenarios in random replication runs at nine signal timings for nine designs impeding green intervals under three design cycles lengths (see Table 5). Each signal timing plan involved three levels of hypothetical pedestrian volumes in pedestrians per hour (pph) and four levels of hypothetical impeding flow volumes in vehicle per hour per lane (vph/ln). The pedestrian volume levels were categorized as low volume, medium volume, and heavy volume. The listed impeding volumes at the rightmost through lane were listed in four incremental impeding flow volume levels for each fixed impeding green interval. The impeding through flows to capacity ratios for the listed four incremental impeding volumes were found to range from 0.70 and not exceed 1.10.

6.4Analyses and Results

For this chapter I studied one phase out of three right-turn FYA permissive phases. The RTOIT FYA DOE was developed in hypothetical impeding green intervals, cycle lengths, impeding flow levels, and pedestrian volumes. The goal of this part of the research was to warrant the efficient implementation of a right-turn FYA phase during an impeding through traffic phase. The MRTT vph is the main MOE to investigate 108 scenarios in various phasing and traffic conditions. Table 6 lists the average RTOIT MRTT per cycle (vpc) derived from the main design of the experiment shown in Table 5 by averaging the MRTT per hour (vph) to the number of cycles and categorizing it into three categories based on an efficiency categorical score. Category 1, highlighted in red, is of all nonefficient scenarios with an average MRTT per cycle equal or less than 2.0 throughputs per cycle. Category 2, highlighted in yellow, is of all the low efficient scenarios with a range of an average MRTT per cycle from 2.1 to 2.9. Category 3, highlighted in green, is of all efficient scenarios that were equal to or more than 3.0 average throughputs per cycle. This step was considered to achieve efficiency-based scores that led to warranting the operational performance of a permissive RTOIT FYA signal phase.

Table 5: RTOIT Design of Experiment (DOE) MRTT per hour (vph)

Impeding phase G/C Ratio	Impeding Flow (vph/ln)	Cycle Length =120 s				Cycle Length =150 s				Cycle length =180 s			
		IGI (s)	Peds. 50 pph	Peds 100 pph	Peds. 300 pph	IGI (s)	Peds. 50 pph	Peds 100 pph	Peds. 300 pph	IGI (s)	Peds. 50 pph	Peds 100 pph	Peds. 300 pph
1/6	L1= 200	IGI= 20 s	73	65	59	IGI= 25 s	61	50	44	IGI= 30 s	62	56	52
	L2= 220		66	61	51		54	50	41		60	54	54
	L3= 240		62	58	49		51	46	38		55	52	49
	L4= 260		58	53	46		48	43	36		52	50	45
1/4	L1= 300	IGI= 30s	105	96	86	IGI= 38 s	88	81	79	IGI= 45 s	90	86	85
	L2= 330		93	87	79		82	78	73		84	82	80
	L3=360		88	82	73		76	73	70		76	75	74
	L4= 390		82	79	71		68	66	65		72	68	66
1/3	L1= 400	IGI= 40 s	126	119	112	IGI= 50 s	124	121	117	IGI= 60 s	122	121	122
	L2= 440		119	115	109		120	109	109		113	107	109
	L3= 480		108	103	104		104	101	100		101	101	100
	L4= 520		98	95	92		99	91	90		93	93	93

Table 6: RTOIT warrants in Average MRTT per Cycle (vpc)

Impeding phase G/C Ratio	Impeding Flow (vph/ln)	Cycle Length =120 s				Cycle Length =150 s				Cycle length =180 s			
		IGI (s)	Peds. 50 pph	Peds 100 pph	Peds. 300 pph	IGI (s)	Peds. 50 pph	Peds 100 pph	Peds. 300 pph	IGI (s)	Peds. 50 pph	Peds 100 pph	Peds. 300 pph
1/6	L1= 200	IGI= 20	2.4	2.2	2.0	IGI= 25	2.5	2.1	1.8	IGI= 30	3.1	2.8	2.6
	L2= 220		2.2	2.0	1.7		2.3	2.1	1.7		3.0	2.7	2.7
	L3= 240		2.1	1.9	1.6		2.1	1.9	1.6		2.7	2.6	2.4
	L4= 260		1.9	1.8	1.5		2.0	1.8	1.5		2.6	2.5	2.2
1/4	L1= 300	IGI= 30s	3.5	3.2	2.9	IGI= 38 s	3.7	3.4	3.3	IGI= 45 s	4.5	4.3	4.3
	L2= 330		3.1	2.9	2.6		3.4	3.2	3.1		4.2	4.1	4.0
	L3=360		2.9	2.7	2.4		3.2	3.0	2.9		3.8	3.8	3.7
	L4= 390		2.7	2.6	2.4		2.9	2.8	2.7		3.6	3.4	3.3
1/3	L1= 400	IGI= 40 s	4.2	4.0	3.7	IGI= 50 s	5.2	5.0	4.9	IGI= 60 s	6.1	6.1	6.1
	L2= 440		4.0	3.8	3.6		5.0	4.5	4.5		5.6	5.4	5.5
	L3= 480		3.6	3.4	3.5		4.3	4.2	4.2		5.1	5.1	5.0
	L4= 520		3.3	3.2	3.1		4.1	3.8	3.8		4.6	4.7	4.7

Initially, to understand the RTOIT warrants function, I must highlight the significant factors that play a role in accomplishing this warrant. The impeding flow was found to be a significant factor to predict the RTOIT MRTT vph (Tarko 2001, HCM 2010, Creasey, Stamatiadis et al. 2011). The RTOIT DOE results show that the impeding flow significantly reduced the MRTT vph. The incremental impeding flow at fixed impeding green intervals increased saturation for the impeding approach and led to a reduction in acceptance gaps. Consequently, the saturated impeding flow declined the MRTT vph and the efficiency score of a permissive RTOIT FYA phase. Figure 16 illustrates the significant decline on MRTT vph led by the impending flow volumes increments at an IGI of 20 seconds.

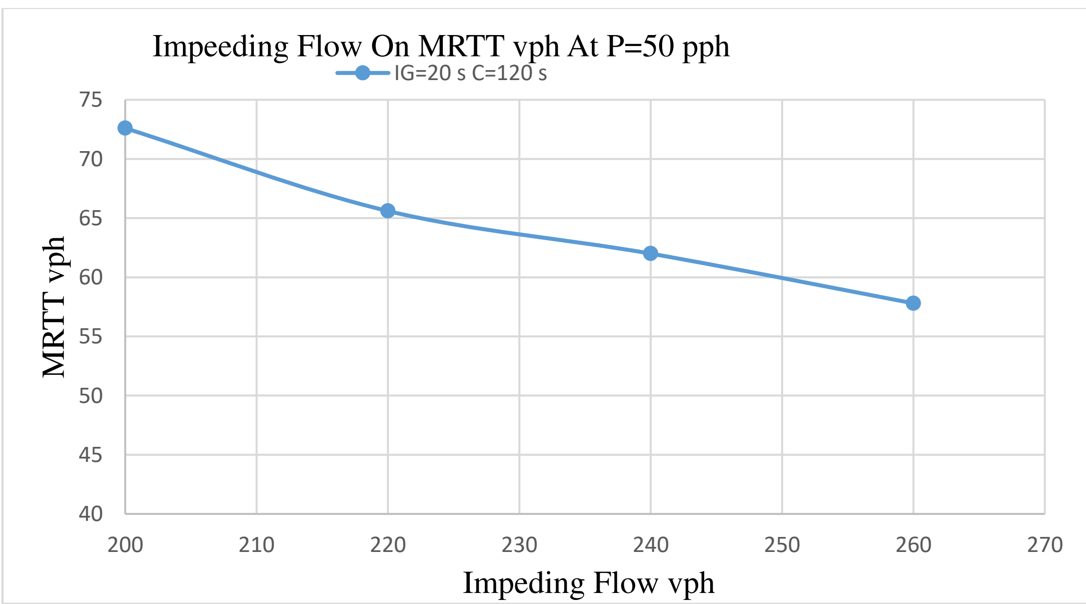


Figure 16. Impeding flow on MRTT vph at P=50 pph.

Moreover, the impeding flow significantly affected the efficiency attribute for an RTOIT FYA phase. The saturated impeding flow at an impeding green interval(s) could significantly change a permissive RTOIT FYA phase attribute from a low efficient categorical score to a non-efficient categorical score. Figure 17 shows a graph that presents the average MRTT per cycle in a y-axis and the impeding flow volumes vph in an x-axis. The graph is illustrated with two dashed lines that represent the low-efficient threshold in a black dashed line and the efficient threshold in a green dash line. Accurately, the area below the black dashed lined represents the nonefficient zone, and the area above the green dashed line represents the efficient zone, while the area in between demonstrates the low efficient zone. It explains how the impeding flow significantly affected the average MRTT per cycle and the efficiency score for a RTOIT FYA signal phase. The graph clearly indicates that a 250 vph impeding flow volume worsened the efficiency score for a permissive right-turn FYA phase from a low efficient to a nonefficient phase at a 20-second impeding green interval. In other words, the results explain that an average of 8 vehicles per cycle at the impeding rightmost lane require 4 seconds of lost time and 2 seconds of headway for each vehicle to depart the intersection at an IGI equal to 20 seconds. Thus, the right-turn traffic will find no accepted gap during the impeding green interval, and only right-turn sneakers could depart the intersection after the impeding green interval.

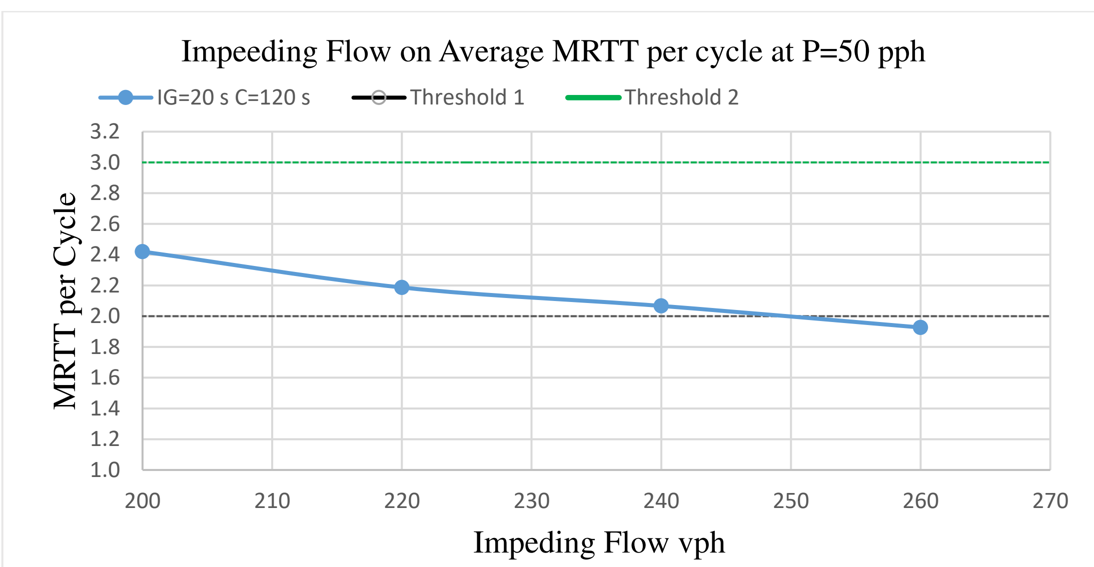


Figure 17. Impeding flow on RTOIT average MRTT per cycle at P=50 pph.

Figure 18 shows two FYA phases' functions at different impeding green intervals and impeding flows. It is clear that the impeding green interval significantly improved the efficiency score of an RTOIT FYA phase. Moreover, the graphs explain clearly that the MRTT per cycle increased by lengthening the impeding green interval. The RTOIT DOE outcomes demonstrated that a permissive RTOIT FYA signal phase at an impeding green interval equal to or more than 40 seconds was efficient. Furthermore, an impeding green interval with less than 25 seconds was not efficient with heavy pedestrian volume and saturated impeding flow. The highway capacity manual states that an interval with a very short permissive green interval will allow only sneakers to depart the intersection (HCM 2010).

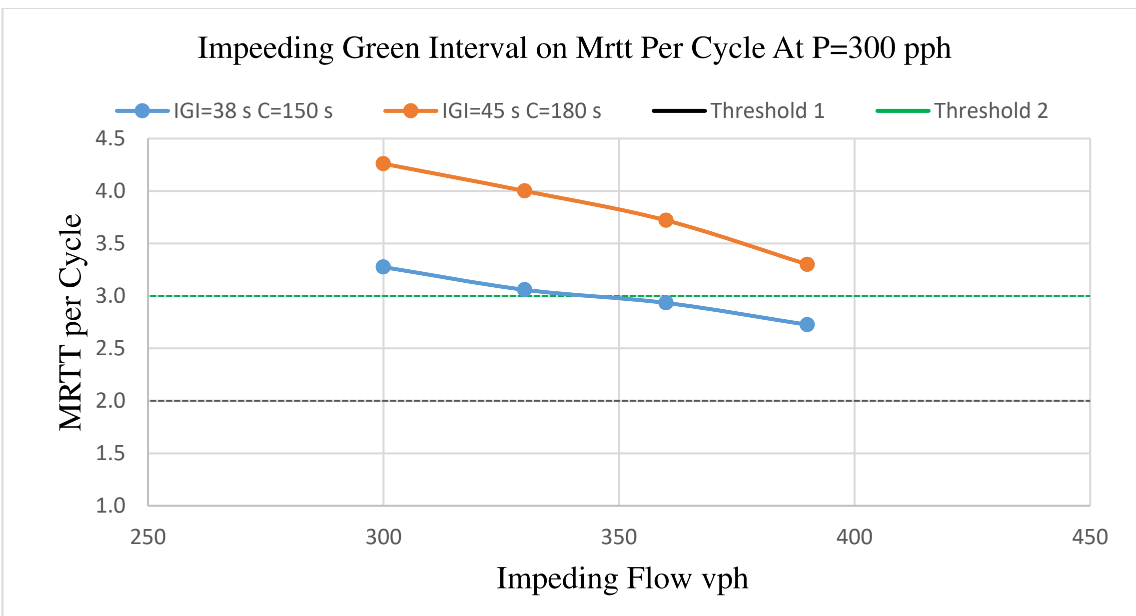


Figure 18. Impeding green interval on RTOIT average MRTT per cycle at P=50.

The right-turn traffic might be impeded by pedestrians crossing the side street or the main street during the impeding through or the adjacent through lane traffic. The RTOIT motorists must completely stop and yield for pedestrians who cross the main street simultaneously with the impeding through traffic. The DOE considered the pedestrian as a significant factor that contributed with other parameters to impede the right-turn operations on the impeding through movement. The research results indicate a clear effect of pedestrian volume on the RTOIT FYA efficiency score especially in short impeding green intervals. The pedestrian volume contributes with the impeding flow vph to worsen the RTOIT efficiency and could lead to forbidding the implementation of a permissive RTOIT FYA phase during a short impeding green interval. Figure 19 clearly indicates that the high pedestrian volume per hour of level 3 resulted in worsening the RTOIT efficiency score from a low efficient to non-efficient attribute at a certain impeding flow in comparison with pedestrian volumes levels 1 and 2. In conclusion, the RTOIT DOE outcomes found that the pedestrian volume had a slight impact on the RTOIT FYA phase efficiency at an impeding green interval more than or equal to 40 seconds.

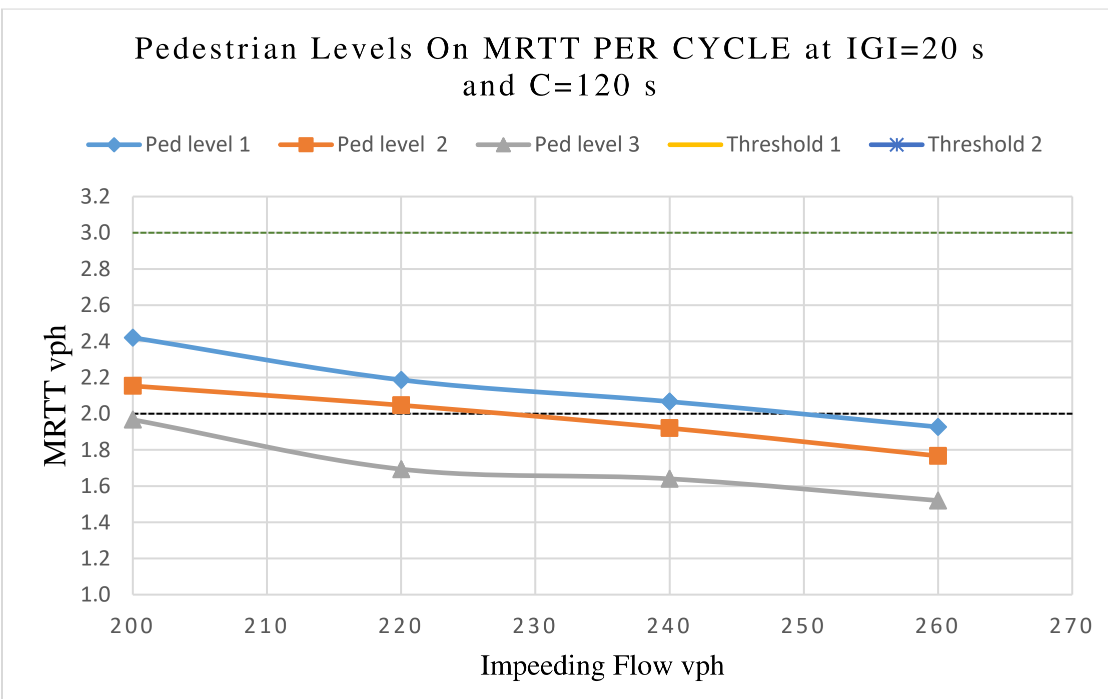


Figure 19. Pedestrian levels on RTOIT average MRTT per cycle at IGI=21 seconds and C=120 seconds.

The cycle length significantly affected the maximum right-turn throughputs per hour (Tarko 2001, Creasey, Stamatiadis et al. 2011). The MRTT per hour at certain green interval was increased by the number of cycles that are a function of cycle length (see Figure 20). I used the average maximum right-turn throughput per cycle to warrant a RTOIT FYA phase. Intuitively, the cycle length factor or cycles number appeared to have no effect on the average MRTT per cycle. The average MRTT per cycle was adopted to measure the average right-turn throughputs in a cycle base that led to assessing the efficient implementation of a permissive right-turn FYA phase based on a certain number of maximum right-turn throughputs or sneakers. Figure 21 illustrates how cycle lengths 120 and 180 were found to have almost similar average MRTT per cycle at a 30-second impeding interval.

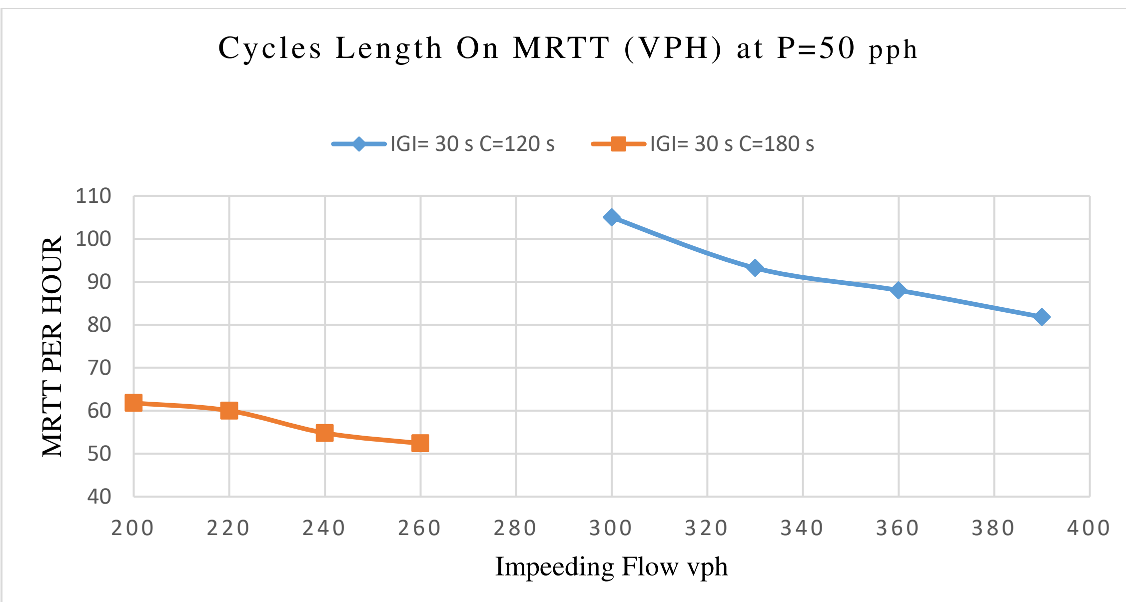


Figure 20. Cycles length on RTOIT MRTT (vph) at P=50 pph.

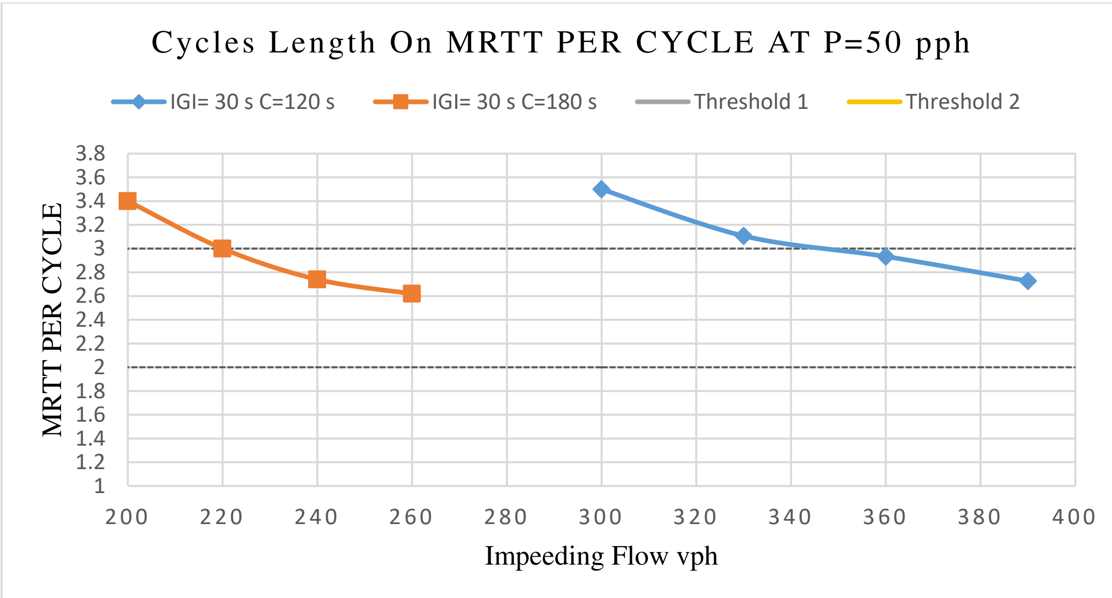


Figure 21. Cycles length on RTOIT average MRTT per cycle at P=50 pph.

6.5 Efficient RTOIT Guidelines

Appendix (A) lists the efficiency guidelines tables for the permissive RTOIT FYA signal phase under three significant parameters: impeding green interval, impeding flow to capacity ratio (IFTCR), and pedestrian volume per cycle. The RTOIT and RTOIL multinomial logit model (MNL) conducted in chapter 9 found that the effect of cycle length on the response average MRTT per cycle attributes was statistically insignificant. Furthermore, the impeding flow was replaced by the IFTCR to accurately measure the impact of the impeding flow for any G/C signal plan. An impeding lane group capacity was estimated using Equation 1. The lost time was considered 4 seconds as listed in the HCM (2010). The efficiency guidelines tables for the permissive RTOIT FYA signal phase warranted finite FYA signal scenarios. Thus, the MNL model listed in chapter 9 was developed to predict the efficiency of a RTOIT FYA signal phase at any phasing and traffic conditions circumstances.

To sum up, I used the RTOIT research to properly assess the efficient implementation of a RTOIT FYA signal phase. There was a crucial need to develop right-turn signal warrants to help decision makers appropriately implement a right-turn FYA signal. The previous studies did not conduct any right-turn signal or right-turn FYA signal warrants. Thus, in this study I successfully developed functional right-turn FYA signal warrants that can be used to assess the efficiency of a RTOIT FYA signal phase using traffic, pedestrian, and phasing parameters. Overall, the DOE results for the RTOIT FYA phase indicated that a RTOIT FYA signal phase was efficient and highly recommended when an impeding green interval equaled or was more than 40 seconds. The yield to pedestrian BOS is strongly recommended to make the right-turn motorists aware to yield for pedestrians walking concurrent with the impeding through traffic. The FYA phase on RTOIT was found not efficient at an impeding green interval less than 25 seconds at a saturated impeding approach. A red indication complimenting the BOS of *No Turn on Red* on the impeding interval was strongly recommended during a non-efficient FYA phase. An impeding phase ranging from 30–35 seconds was found most likely low-efficient. A FYA on RTOIT phase might be implemented during the low efficient phase, yet a BOS of *Yield to Peds* must be applied if pedestrian activity existed.

CHAPTER 7: RIGHT TURN ON IMPEDING LEFT RTOIL WARRANT

7.1 Understanding RTOIL

The RTOIL FYA signal phase is a permissive right-turn movement impeded only by the opposing left-turn traffic. Pedestrian activity is forbidden during this right-turn permissive movement. I assumed that a right-turn motorist turns right on a permissive phase where the right of way is held by the opposing left-turn traffic. Furthermore, the methodology assumed that the number of impeding inbound left-turn lanes (eastbound to northbound) equals the lane's number of the outbound northbound approaches. Therefore, RTOIL motorists rely only on the gaps generated between the impeding eastbound opposing left traffic at the rightmost lane.

7.2 RTOIL Measures of Effectiveness

The maximum right-turn throughput was adopted in many studies to predict the maximum right-turn capacity on permissive right-turn-on-red phases (Creasey et al., 2011; Tarko, 2001). The hourly MRTT and average MRTT per cycle were used to assess the efficiency attribute of a permissive RTOIL FYA signal phase using a set of traffic and phasing parameters. To measure the MRTT during a permissive right-turn phase properly, westbound right-turn lane input volumes were ensured to be at least 1.2 greater than the right-turn throughput volumes. This step was considered to maintain continuous right-turn demands through all right-turn protected and permissive phases.

7.3 Permissive RTOIL Experiment Procedures

Stochastic analysis was conducted using a validated network to develop functional warrants for an efficient RTOIL FYA signal phase. The default Wiedmann 99 driving parameters were held constant through the whole experiment. Steps were accomplished for the RTOIL modeling development under a certain site geometry and listed DOE input data (traffic vehicle features and signal timing plans) to properly warrant the permissive RTOIL FYA phase. These steps are listed in the following sections.

7.3.1 Intersection Geometry

The experiment was designed based on a certain site signalized intersection geometry design and mainly replicated the Alafaya Trail at Lake Underhill Rd. intersection. The northbound approach geometry was designed with two lanes to maintain equal lanes at the eastbound left-turn approach and the northbound approach. The inbound northbound approach was also designed with an exclusive double left-turn and an exclusive right-turn lane. The southbound direction had double through lanes, exclusive double left-turn lanes, and an exclusive right-turn lane. The westbound approach included double through lanes, an exclusive left-turn lane, and a dedicated right-turn lane. The eastbound approach had double through lanes, exclusive double left-turn lanes, and an exclusive right-turn lane. Figure 22 illustrates the studied signalized intersection layout developed using VISSIM vision 10.02 package.

Figure 22. RTOIL intersection geometry design.

The right-turning motorists at the dedicated westbound lane had to yield to the impeding traffic at the eastbound left-turn lanes before proceeding through the intersection during the RTOIL permissive phase. The westbound dedicated right-turn lane was designed to allow the implementation of an exclusive PPRT phasing signal.

7.3.2 DOE Significant Parameters Considered

The RTOIL DOE was developed to measure the MRTT vph in three parametric factors. The MRTT per hour MOE was a key used to warrant the permissive FYA during the RTOIL. Those listed factors were found to significantly impact the maximum throughput on permissive right-turn on red phases (Tarko 2001, HCM 2010, Creasey, Stamatiadis et al. 2011). The three significant factors are:

- Impeding vehicular flow in the rightmost lane (vph);
- Expected signal cycle (s); and
- The impeding green interval (IGI) (s).

The designed impeding vehicular incremental volumes were obtained and listed in the DOE in multiple levels for an impeding GI and cycle length.

7.3.3 Signal Timing

The RTOIL design of the experiment involves 12 hypothetical signal timing plans. A hypothetical signal timing listed in the RTOIL DOE was optimized on an impeding designed EB left-turn green interval, a designed cycle length, and impeding eastbound left-turn flow volume. All signal timing plans ran as an 8-phase intersection, with four protected left-turn phases, and a protected/permissive right-turn phase at the westbound approach. The studied PPRT phase (westbound to northbound movement) was designed to allow functioning of a protected green arrow and permissive FYA indications in VISSIM. The protected green arrow is displayed during the nonconflicting southbound left turn phase while the U-turn is prohibited. The FYA indications are displayed during the adjacent westbound through, the impeding northbound through, and the impeding eastbound left-turn movements. Synchro 9.0 software was used to optimize 12 hypothetical signal timing plans as a pretimed control system in three cycle lengths (s), and four impeding eastbound left-turn G/C plans. Pretimed control was adopted in this experiment with fixed green phases to fulfill the RTOIL DOE's signal timing categories.

7.3.4 RTOIL VISSIM Coding Procedures

Similar to RTOIT, VISSIM with overlaps coding was used to allow the implementation of the PPRT FYA phasing practice at the westbound approach. The right-turn phasing code included four right-turn phases: overlap, RTOIT, RTOIL, and RTOAT. The right-turn throughputs were collected at a second by second time basis for one hour. Then, the RTOIL MRTT vph was obtained by accumulating all throughputs occurring simultaneously with the impeding opposing eastbound left-turn phase based on the signal display outputs provided in VISSIM. Finally, I used Excel spreadsheets to count the MRTT vph for a RTOIL phase scenario.

7.4 Right Turn on Impeding Left-turn RTOIL DOE

The MRTT vph MOE results were obtained for various impeding left-turn flow volumes at several signal timing plans to assess a permissive RTOIL FYA phase. The design of the experiment resulted in 48 scenarios in a set of random seeds replications at 12 signal timings for 12 impeding green intervals under three cycles length (see Table 7). The impeding flow volumes were listed in four incremental impeding volumes (vph/ln) for each IGI group in the DOE. The impeding volumes to capacity ratios at the rightmost left lane were less than 1.3 and more than 0.75.

7.5 Analysis and Results

The RTOIL FYA signal phase study conducted various traffic conditions and signal timing plans based on microsimulation analysis. Variables like impeding green interval, impeding flow, and cycle length were involved to design an experiment resulting in almost 50 scenarios under various traffic conditions and signal timing plans. The MRTT vph was the main MOE used to warrant the efficient implementation of a permissive RTOIL FYA phase. The averaged MRTT per cycle was the main key used to assess a permissive FYA phase efficiency attribute. The MRTT vph results obtained from the DOE MOE in Table 7 were relisted in Table 8 in average MRTTs per cycle. The MRTT per cycle results were categorized in three categorical scores to allow assessing a RTOIL FYA phase efficiency score. Category one in red represents the non-efficient scenarios with an average MRTT per cycle less or equals to two throughputs. Category 2 illustrates the low-efficient scenarios in yellow that resulted in an average MRTT per cycle between 2.1 and 2.9 throughputs. Category 3 represents the efficient scenarios in green with an average MRTT per cycle equal to three throughputs or more.

Table 7: RTOIL Design of Experiment (DOE) in MRTT (vph)

Impeding G/C Ratio	Impeding Flow (vph)	IGI (s)	C=120 s	IGI (s)	C=150 s	IGI (s)	C=180 s
1/10	**L1= 110**	**IGI=12 s**	56	**IGI=15 s**	51	**IGI=18 s**	46
	L2= 130		51		41		40
	L3=150		43		37		35
	L4= 160		42		33		33
1/8	**L1= 140**	**IGI=15 s**	58	**IGI=19 s**	52	**IGI=22 s**	52
	L2= 170		52		44		42
	L3=180		45		39		40
	L4= 190		42		37		38
1/6	**L1=200**	**IGI=20 s**	63	**IGI=25 s**	65	**IGI=30 s**	57
	L2= 220		58		54		52
	L3= 240		53		52		47
	L4= 260		44		45		43
1/4	**L1= 300**	**IGI=30 s**	84	**IGI=37 s**	78	**IGI=45 s**	79
	L2= 330		78		68		68
	L3=360		72		61		61
	L4= 390		61		51		54

Table 8: RTOIL Warrants in Average MRTT per Cycle (vpc)

Impeding G/C Ratio	Impeding Flow (vph/ln)	IGI (s)	C=120 s	IGI (s)	C=150 s	IGI (s)	C=180 s
1/10	L1= 110	IGI=12 s	1.9	IGI=15 s	2.1	IGI=18 s	2.3
	L2= 130		1.7		1.7		2.0
	L3=150		1.4		1.5		1.8
	L4= 160		1.4		1.4		1.6
1/8	L1= 140	IGI=15 s	1.9	IGI=19 s	2.2	IGI=22 s	2.6
	L2= 170		1.7		1.8		2.1
	L3=180		1.5		1.6		2.0
	L4= 190		1.4		1.5		1.9
1/6	L1=200	IGI=20 s	2.1	IGI=25 s	2.7	IGI=30 s	2.9
	L2= 220		1.9		2.3		2.6
	L3= 240		1.8		2.2		2.4
	L4= 260		1.5		1.9		2.2
1/4	L1= 300	IGI=30 s	2.8	IGI=37 s	3.2	IGI=45 s	3.9
	L2= 330		2.6		2.8		3.4
	L3=360		2.4		2.5		3.0
	L4= 390		2.0		2.1		2.7

The RTOIL DOE outcomes indicate that the categorical scores based on efficiency were mostly nonefficient or low efficient for the majority of the impeding intervals even at low impeding flow volumes (see Table 8). The RTOIL DOE results demonstrated that the impeding flow volumes increments worsen the MRTT vph and the efficacy score for a permissive RTOIL signal phase. See Figures 23. Moreover, the incremental impeding flow at fixed impeding green interval saturated an impeding approach and likely reduced the accepted gaps and throughputs during a permissive right-turn phase.

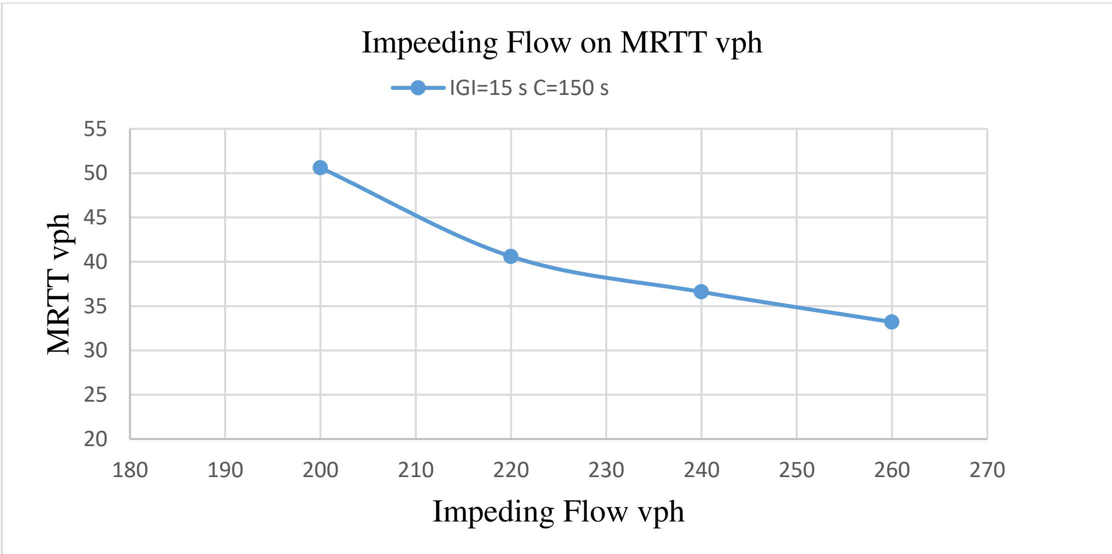


Figure 23. Impeding flow on RTOIL MRTT vph.

Figure 24 shows a graph that coordinates the average MRTT per cycle in y-axis and the impeding flow volumes, vph, in x-axis. The graph is illustrated by a dashed line representing the nonefficient threshold. The area below the black dashed line represents the nonefficient zone, and the area above demonstrates the low efficient zone. It shows how the impeding flow increments significantly worsen the average MRTT per cycle and the efficiency score from a low efficient to nonefficient phase when it is impeded by almost 210 vph at an impeding green interval equal to 20 seconds. A simple calculation proves that an average of 8 vehicles per cycle at the impeding rightmost lane require 4 seconds of lost time and 2 seconds of headway for each vehicle to depart the intersection at an IGI equal to 20 seconds. Consequently, the right-turn traffic will find not enough of an accepted gap during the impeding green interval, and only right-turn sneakers could depart the intersection after the impeding green interval.

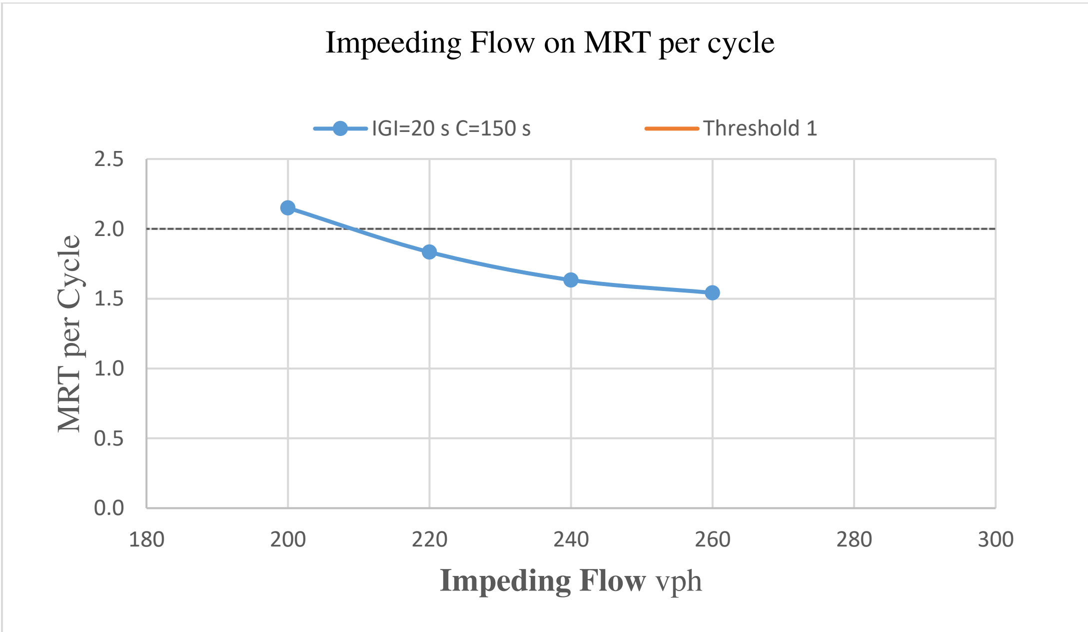


Figure 24. Impeding flow on RTOIL average MRTT per cycle.

The impeding green interval has significant implication on the MRTT vph and the averaged MRTT per cycle. An extended impeding green interval significantly demonstrates a clear improvement of the MRTT per cycle and the efficiency score for a permissive RTOIL FYA signal phase, as illustrated in Figure 25. Overall, the permissive RTOIL FYA phase was observed efficiently feasible at an impeding green interval equal to or longer than 45 seconds. The RTOIL warrant outcomes found that a permissive RTOIL FYA was not warranted at an impeding green interval equal to or less than 25 seconds. It was found that a short impeding green interval discharged only sneakers during a permissive phase (HCM 2010).

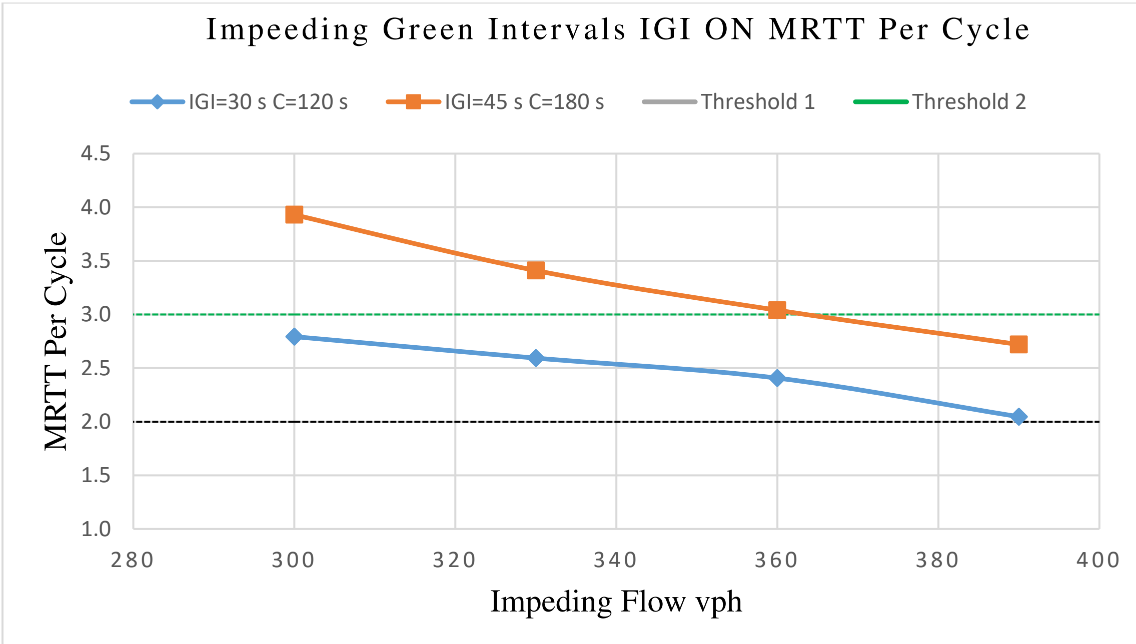


Figure 25. Impeding green intervals on RTOIL average MRTT per cycle.

The cycle length was found to significantly affect the maximum right-turn throughputs MRTT vph (HCM 2010). The RTOIL DOE results clearly proved the impact of cycle length on the MRTT vph results as well (see Table 8 and Figure 26). However, the RTOIL averaged MRTT per cycle results were found to be similar during equal impeding green intervals at different cycle lengths (see Figure 27). Intuitively, I found the average MRTT per cycle results most likely consistent during equal impeding green intervals for various cycle lengths and at the same impeding flow volumes.

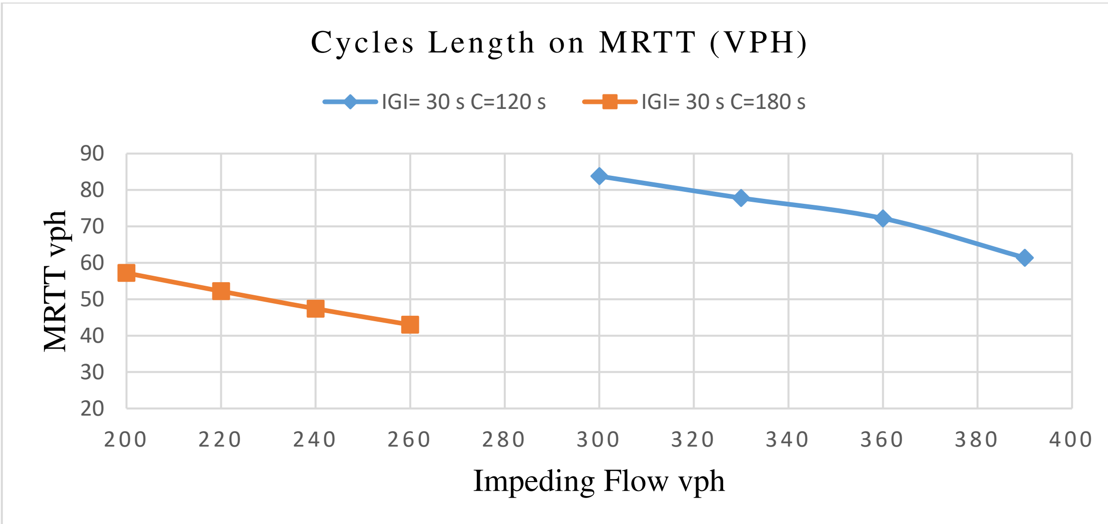


Figure 26. Cycle length on RTOIL MRTT vph.

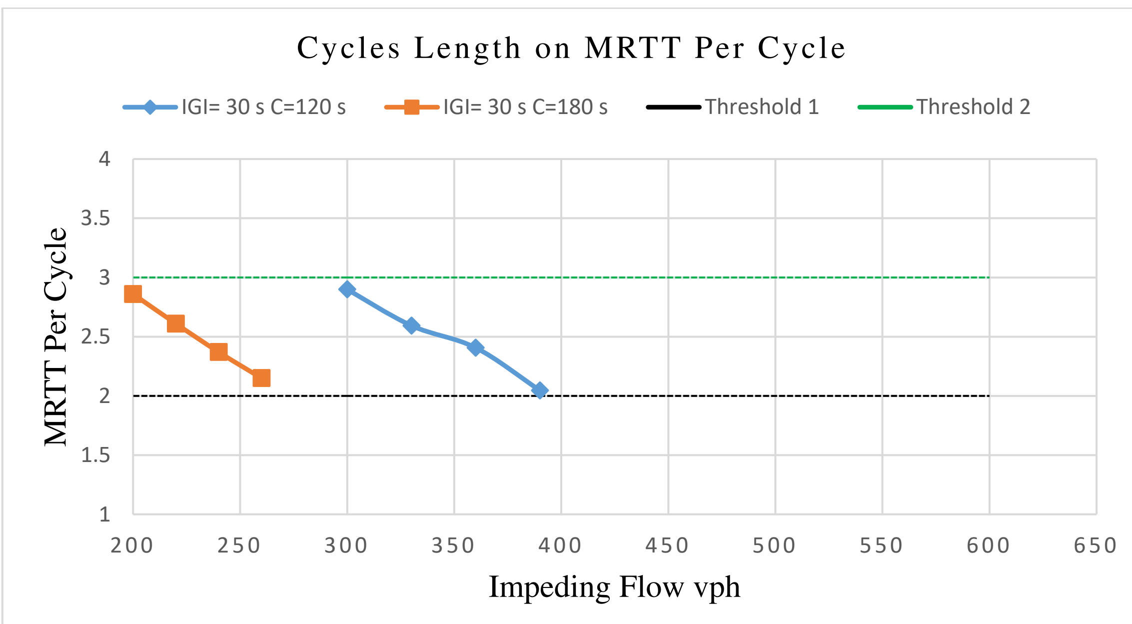


Figure 27. Cycle length on the average MRTT per cycle.

7.6 Efficient RTOIL Guidelines

Appendix B lists guideline tables-based efficiency for the permissive RTOIL FYA signal phase. The RTOIL FYA signal phase guidelines are represented using two significant parameters:

the impeding green interval and IFTCR. The discrete choice model developed in chapter 9 found the cycle length a statistically insignificant variable. The efficiency guidelines tables were observed applicable only for limited FYA signal scenarios. Thus, an MNL model was developed in chapter 9 to applicably predict any phasing scenario for a permissive RTOIL FYA signal phase.

In conclusion, the experiment outcomes were unique and appropriately assessed the efficient implementation for a right-turn FYA signal phase during the impeding left phase. The impeding green interval and IFTCR had the appropriate parameters to warrant and predict the efficiency of a RTOIL FYA signal phase. The previous studies had not conducted any right-turn signal or right-turn FYA signal warrants. Thus, in this research I successfully developed functional right-turn FYA signal warrants used to predict the efficient application of a RTOIL FYA signal phase using two traffic and phasing parameters. Overall, the RTOIL MRTT per cycle results were efficient only at an impeding interval equal to or more than 45 seconds. The RTOIL FYA phase was found nonefficient at an impeding green interval less than 25 seconds and low efficient at an impeding green interval from 30–40 seconds. A red indication complemented with a BOS of *No Turn on Red* on the impeding interval is strongly recommended during a nonefficient RTOIL phase.

CHAPTER 8: RIGHT TURN ON ADJACENT THROUGH RTOAT WARRANT

8.1 Understanding RTOAT

Motorists turning right on green must yield to pedestrians crossing on a walk signal for the side street (Herman 2002). Therefore, Yield to Pedestrians or Pedestrians Watch for Turning Vehicle signs are commonly used to mitigate pedestrians' risks related to turning traffic (Zegeer, Opiela et al. 1982). Pedestrians are usually assigned to cross simultaneously with the through-traffic movement where a vehicle or bicyclist must yield before turning right (FHWA 2015 b). RTOAT is a protected right-turn phase from vehicular traffic for which right-turn traffic must yield to pedestrians crossing the side street. To warrant the permissive FYA on the adjacent lanes through green, the research fulfilled the essential factors associated with RTOAT throughput blockage. Moreover, the methodology assumed that the right-turn adjacent lanes' green interval equals the pedestrian walking interval (PWI) and flashing *Don't Walk* (FDW) interval. If the pedestrian total phase (PWI + FDW) is shorter than the right-turn adjacent lanes phase, the RTOAT movement after the pedestrian total phase vanished was considered protected because no pedestrian movement was allowed. The MRTT vph might be affected by the pedestrian volume crossing the side street and conflict with the right-turn traffic during a permissive RTOAT FYA phase.

8.2 RTOAT Measures of Effectiveness

Similar to that of RTOIT and RTOIL, MRTT vph is the primary measure of effectiveness (MOE) used in the DOE to warrant the permissive RTOAT FYA phase. The maximum right-turn throughput was presented in many studies to obtain the right-turn capacity on a permissive right-turn phase (Tarko 2001, Creasey, Stamatiadis et al. 2011). The average MRTT per cycle derived from the DOE MOE (MRTT vph) was used to assess the efficient implementation of the permissive FYA during a RTOAT FYA signal phase using a set of significant variables. To appropriately obtain accurate MRTT vph results, the exclusive studied right-turn input volumes were ensured to be at least 1.2 times the right-turn throughput for each scenario listed in the RTOAT DOE to fulfill continuous traffic right-turn demands through all the PPRT phases.

8.3 Permissive RTOAT Experiment Procedures

I conducted stochastic analysis to develop the RTOAT experiment using multiple hypothetical networks in a non-calibrated microsimulation model. The VISSIM software was used by holding the default Wiedmann 99 driving parameters constant through the whole experiment. Many procedures were undertaken for the RTOAT FYA warrants development under several hypothetical geometry designs, impeding pedestrian volumes, and phasing plans. To achieve the research objective, a number of steps were developed and described in detail in the following sections:

8.3.1 Intersection Geometry

The right-turn traffic at the dedicated right-turn westbound lane must yield for pedestrians crossing the side street before proceeding through the intersection during a permissive RTOAT FYA phase. The FDW interval is a function of the crossed street's length and pedestrians' speed. Thus, The RTOAT's DOE was developed to involve three hypothetical geometrical designs based on three side street crosswalks. The three geometrical designs were built to fulfill three FDW intervals. The first geometry layout was designed with triple lanes for the cross-street northbound and southbound approaches to maintain a 25-second FDW interval. The second geometrical design was developed on a double-lane for the northbound and southbound approaches to allow a functioning 15-second FDW interval. The third geometrical design was built to fulfill the shortest FDW at a 10-second interval on a single lane each way at the southbound and northbound approaches. The northbound and southbound approaches were designed with an exclusive left-turn lane, a shared lane for the single lane and double-lane designs, and an exclusive right-turn lane for the triple lane design. The westbound approach was designed on double through lanes, an exclusive left-turn lane, and a dedicated right-turn lane. The eastbound approach had double through lanes, an exclusive left-turn lane, and an exclusive right-turn lane. The westbound dedicated right-turn lane was designed to allow the implementation of an exclusive PPRT phasing signal. Figures 28–30 illustrate the RTOAT DOE's intersections geometries developed using VISSIM vision 10.02 package.

Figure 28. RTOAT single lane geometry design.

Figure 29. RTOAT double Lane geometry design.

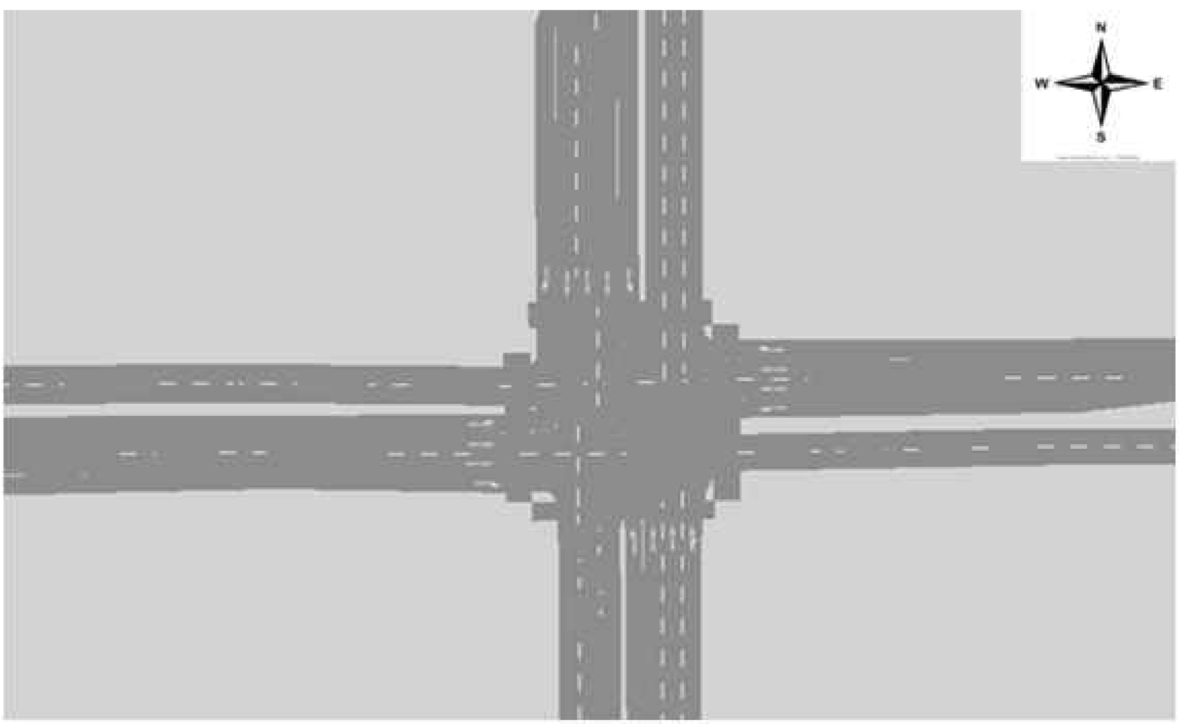


Figure 30. RTOAT triple Lane geometry design.

8.3.2 DOE Significant Parameters Considered

I review the previous studies on PPRT phasing to obtain the significant factors found to implicate the performance of a permissive right-turn phase during the adjacent through green movement. The literature review showed insufficient research studied the factors that affect the right-turn throughputs on the permissive circular green. Thus, the research primarily considered four variables in the RTOAT DOE to measure the right-turn throughputs (MRTT vph). The variables are listed as follows:

- Impeding pedestrian volume (pph);
- Expected signal cycle (s);
- Impeding PWI interval (s); and
- FDW interval (s).

8.3.3 Signal Timing

Eighteen hypothetical signal timing plans were listed in the RTOAT FYA DOE. Each signal timing plan was optimized based on a designed impeding pedestrian total phase (PWI + FDW intervals), a designed cycle length, and an adjacent lane flow volume. The RTOAT methodology assumed equal phases for the right-turn adjacent lane's green interval and the pedestrian's total phase (PWI + FDW). All signal timing plans ran as an 8-phase intersection, with four protected left-turn phases, and a protected/permissive right-turn phase at the westbound approach. The studied PPRT phase (westbound to northbound movement) was designed to allow functioning of a protected green arrow and permissive FYA indications in VISSIM 10.02. The protected green arrow is displayed during the non-conflicting southbound left turn phase while the U-turn is prohibited. The FYA indications are displayed during the adjacent westbound through, the northbound through, and the eastbound left-turn movements. I used Synchro 9.0 software to optimize 18 signal timing plans at three designed cycle lengths and six designed impeding pedestrian's total phase intervals (PWI + FDW). The pedestrian phases were designed as a concurrent pedestrian phase that allows the pedestrian to walk paralleled with the adjacent through traffic. Accurately, the impeding pedestrian phase was optimized to receive the walking phase display immediately as the adjacent westbound through lanes received the green indication. The impeding pedestrian phases were designed with PWI at 5 and 10 seconds and Flash Don't Walk (FDW) intervals at 10, 15, and 25 seconds. Pretimed control was adopted in this research with fixed green phases to fulfill the RTOAT DOE's signal timing plans.

8.3.4 RTOAT VISSIM Coding Procedures

As with RTOIT and RTOIL, VISSIM with an overlaps coding tool was used to allow the function of PPRT FYA phasing practice at the westbound approach. The right-turn phasing was designed to display four right-turn phases: protected overlap phase and permissive RTOIT, RTOIL, and RTOAT phases. The right-turn throughput was collected at a second-by-second time basis for 1 hour to obtain the MRTT vph results during the permissive RTOAT FYA phase. I used Excel spreadsheets to accumulate the right-turn throughputs occurring simultaneously with the adjacent through lane phase based on the signal display outputs provided in VISSIM.

8.3.5 Right-Turn on Adjacent THROUGH RTOAT DOE

The RTOAT DOE listed 72 scenarios under 18 signal timing plans at multiple levels of hypothetical impeding pedestrian volumes per cycle (ppc). Each hypothetical signal timing plan was optimized in a designed cycles' length and a designed impeding pedestrian phase comprising the PWI, and FDW intervals or a designed adjacent through green interval. The pedestrian phases were presented in two PWI intervals at 5 seconds and 10 seconds and three FDW intervals at 10, 15, and 25 seconds. Table 10 lists the RTOAT MRTT per hour (vph) results obtained from the microsimulation in vehicle per hour (vph) using a random set of replications runs for each scenario.

8.4 RTOAT Analysis and Results

The permissive RTOAT FYA was designed to achieve functional RTOAT FYA warrants at various aspects of pedestrian phasing and volumes by conducting a stochastic analysis. The analysis involved three hypothetical geometric designs, hypothetical pedestrian volumes, and a number of signal timing plans to appropriately warrant the permissive FYA phase in different pedestrian volumes and crosswalk lengths circumstances. The developed RTOAT DOE presented limited phasing and pedestrian volumes plans that appear to be the most common practices in the field.

Table 10 lists the averaged RTOAT MRTT per cycle results measured by averaging the MRTT per hour (vph), obtained from the DOE MOE for the number of cycles to appropriately assess the efficiency attribute for a permissive RTOAT phase. The MRTT per cycle results were categorized into two categorical scores based on efficiency. Category one represents the low-efficient (LE) scenarios in yellow that resulted in an average MRTT per cycle between 2.1 and 2.9 throughputs. Category 2 represents the efficient (E) scenarios in green with an average MRTT per cycle equal to three throughputs or more. The listed multiple levels of impeding pedestrian per cycle volumes were measured as throughputs before collecting RTOIT MRTT for each scenario using the VISSIM software to ensure accurate DOE input and output outcomes.

Table 9: RTOAT Design of Experiment (DOE) in MRTT (vph)

Ped. Walking Interval (s)	Pedestrians per cycle (ppc)	FDW = 10 s (single lane)			FDW = 15 s (double lanes)			FDW = 25 s (Triple lanes)		
		C=120 s	C=150 s	C=180 s	C=120 s	C=150 s	C=180 s	C=120s	C=150 s	C=180 s
PWI= 5 s	**10**	81	69	56	92	74	60	150	122	106
	20	77	65	49	88	72	58	148	118	102
	30	69	60	47	86	70	55	144	115	100
	40	66	57	46	83	68	53	139	112	97
PWI =10 s	**10**	93	74	63	118	101	82	170	138	118
	20	88	70	59	113	91	74	162	135	111
	30	78	66	59	102	85	73	158	130	109
	40	74	64	55	97	83	70	152	123	104

Table 10: RTOAT Warrants in Average MRTT per Cycle

Ped. Walking Interval (s)	Pedestrians per cycle (ppc)	FDW = 10 s (single lane)			FDW = 15 s (double lanes)			FDW = 25 s (Triple lanes)		
		C=120 s	C=150 s	C=180 s	C=120 s	C=150 s	C=180 s	C=120s	C=150 s	C=180 s
PWI = 5 s	**10**	2.7	2.9	2.8	3.1	3.1	3.0	5.0	5.1	5.3
	20	2.6	2.7	2.4	2.9	3.0	2.9	4.9	4.9	5.1
	30	2.3	2.5	2.4	2.9	2.9	2.8	4.8	4.8	5.0
	40	2.2	2.4	2.3	2.8	2.8	2.7	4.6	4.7	4.9
PWI =10 s	**10**	3.1	3.1	3.2	3.9	4.2	4.1	5.7	5.8	5.9
	20	2.9	2.9	3.0	3.8	3.8	3.7	5.4	5.6	5.6
	30	2.6	2.7	3.0	3.4	3.6	3.7	5.3	5.4	5.5
	40	2.5	2.7	2.7	3.2	3.4	3.5	5.1	5.1	5.2

Pedestrian volume significantly affects the right-turn operational performance (HCM 2010, Hurwitz, Monsere et al. 2018). The average MRTT per cycle results were found mostly to have more than two throughputs at sufficient impeding pedestrian intervals. The efficiency score was found efficient at a long impeding pedestrian signal interval and low efficient at short impeding pedestrian signal interval impeded by heavy pedestrian volume. The right-turn critical throughputs on the RTOAT were found not only as benefits of change intervals but also of FDW intervals. An FDW interval is designed to forbid pedestrians from starting walking and to complete crossing for those who had already started walking but did not make it to the end of the crosswalk. Also, the right-turning motorists were observed using the gaps between pedestrians during the impeding pedestrian intervals or using the change and clearance intervals to make a right turn on a permissive right-turn phase.

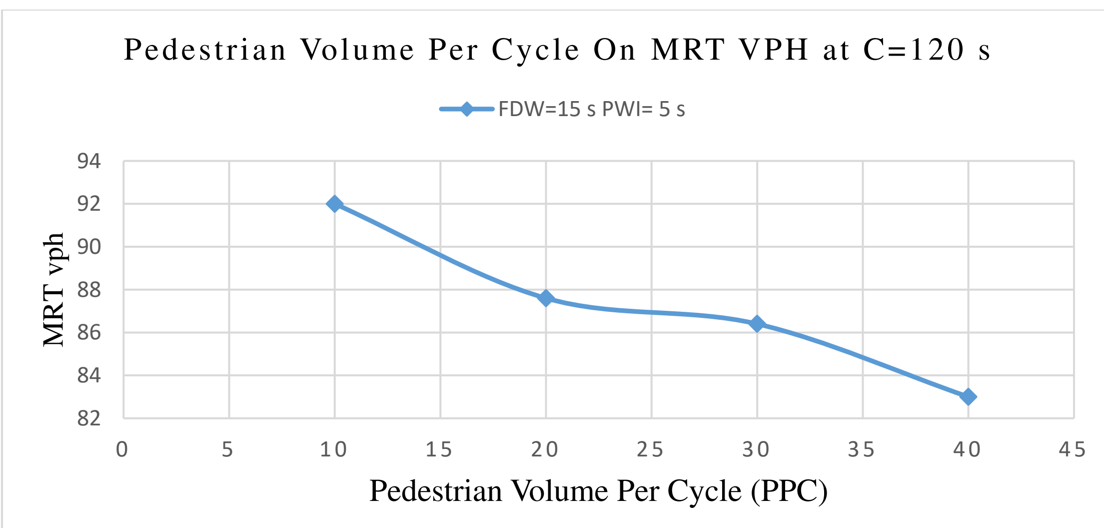


Figure 31. Pedestrian volume per cycle on MRTT vph at c=120 s.

Overall, the results showed that the pedestrian volume per cycle was a significant variable that impeded right-turn throughputs during an RTOAT phase. Moreover, the DOE results present a significant decline on the MRTT vph caused by the incremental pedestrian volumes per cycle.

Figure 31 presents clearly the drop in the MRTT vph caused by the heavy pedestrian volumes per cycle increments. Apparently, the impeding pedestrian intervals, WPI and FDW, were observed to improve the MRTT vph and the efficiency score of a permissive RTOAT phase. The DOE results clearly demonstrated a significant change of the MRTT vph at long impeding pedestrian walk PDW and FDW intervals. Figure 32 represents two charts at multiple levels of pedestrian volume per cycle represented by the x-axis. Chart a illustrates two RTOAT FYA phases' functions at different PWI intervals and a fixed FDW interval. The MRTT per hour at a 10-second PWI outperformed the 5-second PWI interval. Similarly, the impeding pedestrian FDW interval was found to increase the MRTT per hour on certain pedestrian volumes per cycle. Chart b illustrates two RTOAT FYA phases' functions at different FDW intervals and a fixed PWI interval. It was clearly observed that the 25-second FDW interval outperforms the 10-second FDW interval.

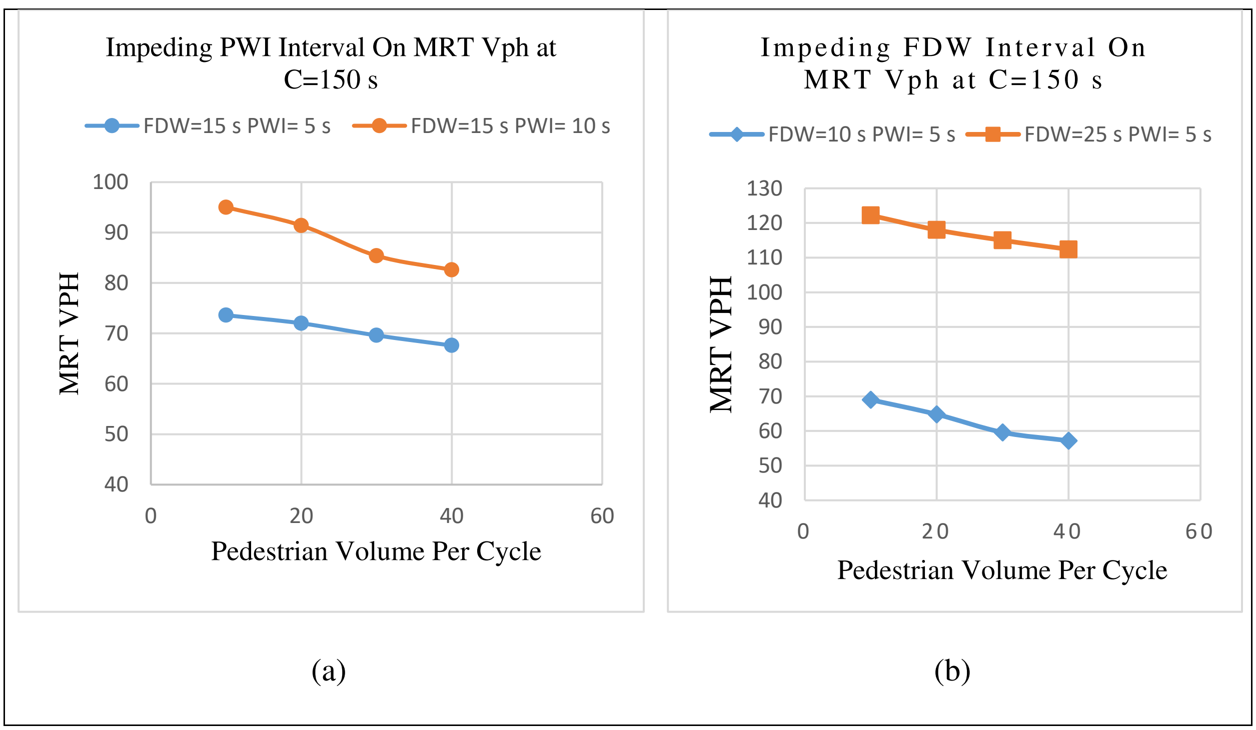


Figure 32. PWI and FDW intervals on MRTT vph.

Figure 33 presents the average MRTT per cycle represented by the y-axis for three RTOAT FYA phases' functions at three pedestrian total intervals under a set of incremental pedestrian volumes per cycle represented by the x-axis. The chart is illustrated with a dashed green line that represents an efficient threshold. Specifically, the area above the green dashed line represents the efficient zone, while the area below the green dashed lined represents the low efficient zone. The graph clearly demonstrates that a 30-second total pedestrian interval improved the average MRTT per cycle and the efficiency score for a permissive RTOAT FYA phase in comparison to the other shorter phases. The total impeding pedestrian phase consisting of PWI and FDW intervals was found to play a role and increased the probability of implementing an efficient RTOAT FYA signal phase.

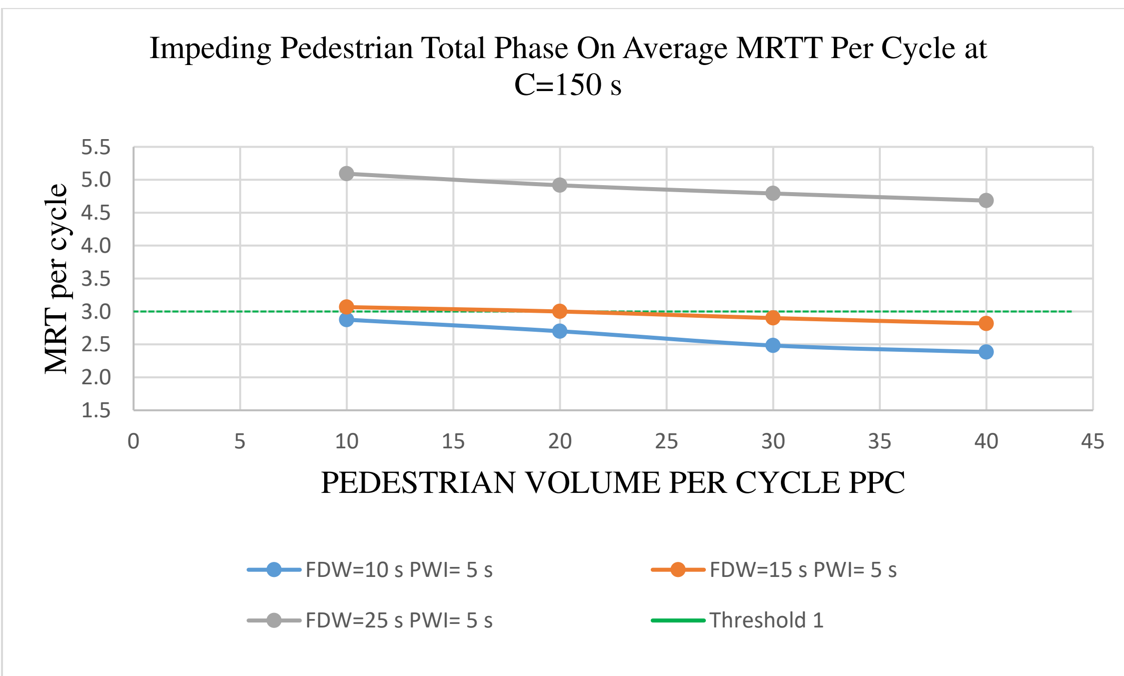


Figure 33. Impeding pedestrian total phase on average MRTT per cycle at c=150 s.

The cycle length was a significant variable contributing to other factors to properly measure and predict the maximum right-turn throughputs MRTT vph of a permissive right-turn phase

(Tarko 2001, HCM 2010, Creasey, Stamatiadis et al. 2011). The collected results from the DOE demonstrated a significant impact of cycle length on the RTOAT MRTT vph (see Table 9 and Figure 34). The averaged MRTT per cycle measurement was adopted in this study to assess the efficiency of a permissive FYA signal phase. The average MRTT per cycle results behaved similarly based on the efficiency matter during equal impeding pedestrian phases for different cycle lengths (see Figure 35). The average MRTT per cycle results were mostly consistent at equal impeding pedestrian intervals for various cycle length plans and with the same impeding pedestrian per cycle volumes.

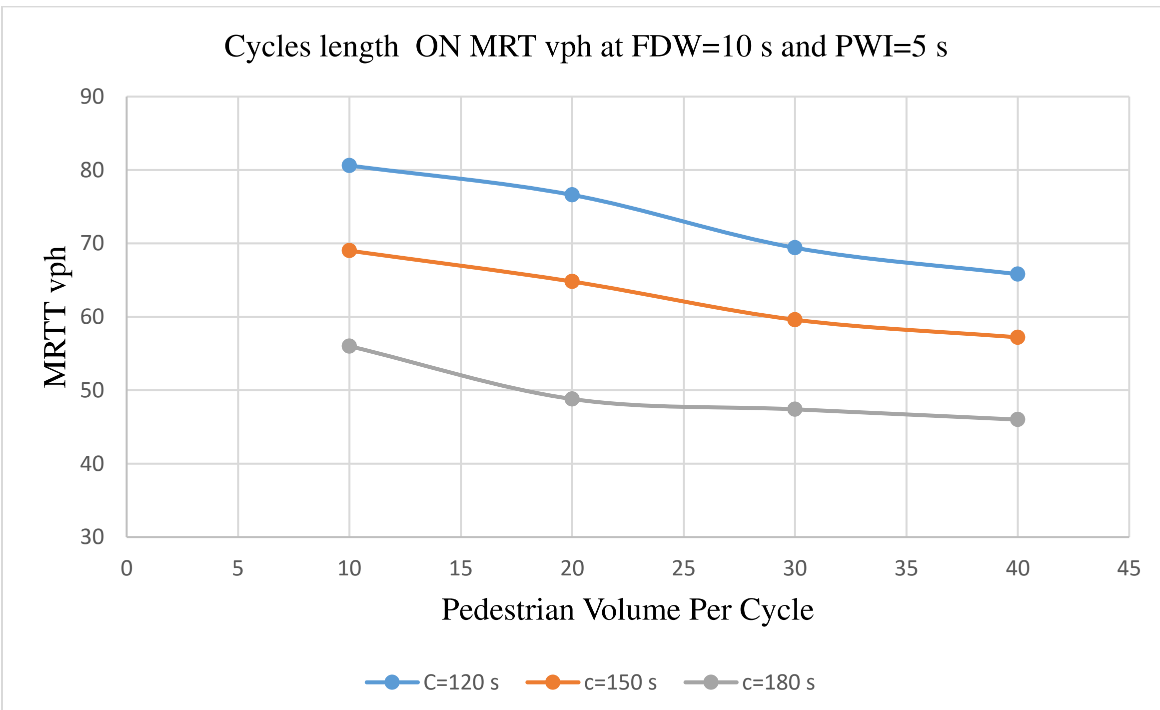


Figure 34. Cycles length on MRTT vph at FDW=10 seconds and PWI=5 s.

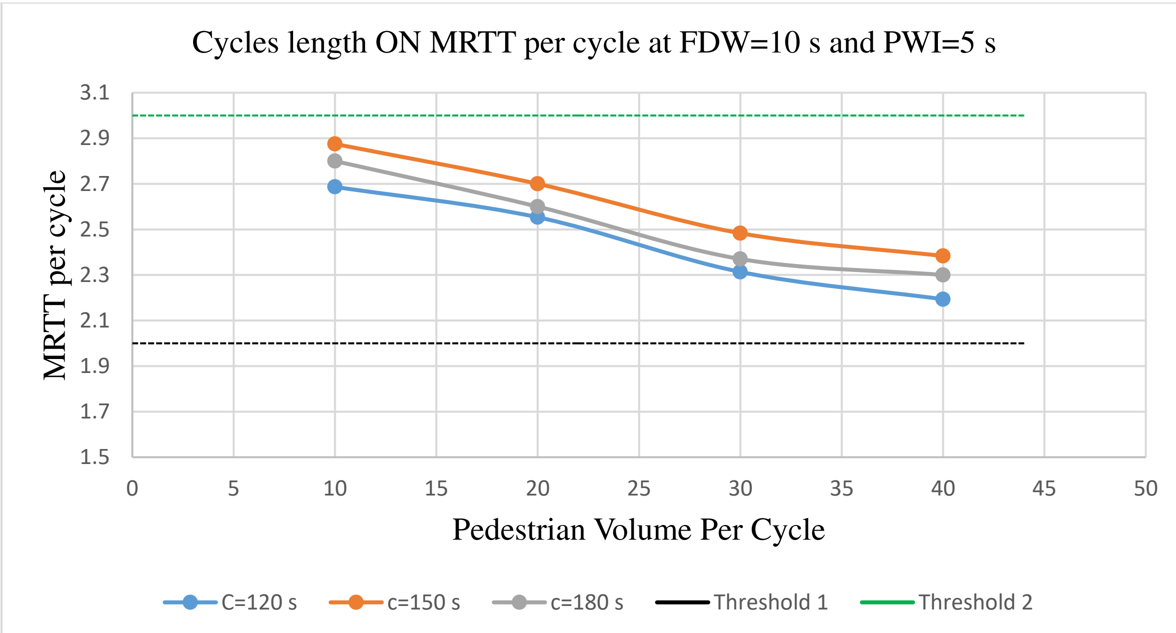


Figure 35. Cycles length on MRTT per cycle at FDW=10 seconds and PWI=5 s.

8.5 Efficient RTOAT Guidelines

The efficiency guidelines table for the permissive FYA signal phase on the adjacent through green is listed in Appendix B. It warrants a permissive RTOAT FYA signal phase using three significant parameters: impeding pedestrian walk interval, impeding FDW interval, and impeding pedestrian per cycle volume. The RTOAT MNL model developed in Chapter (9) found that the cycle length statistically was an insignificant variable. A RTOAT MNL model was developed in chapter 9 to practically predict the efficiency attribute of a permissive RTOAT FYA signal phase at any pedestrian volume and phasing conditions.

I conducted the experiment to efficiently warrant a right-turn FYA signal phase during the adjacent through lane phase. The literature showed a lack in study of the permissive right turn on green or RTOAT FYA signal phase. Thus, I conducted a study to figure out the significant variables that affect the performance of a RTOAT FYA or a right turn on green signal phase. The study found that pedestrian volume and pedestrian phasing significantly play a role to warrant the efficient use of a RTOAT FYA phase. Finally, I successfully developed functional right-turn FYA signal warrants that help decision makers to predict the efficiency of a RTOIL FYA signal phase using two pedestrian volume and phasing parameters. The RTOAT MRTT per cycle results were found either low or highly efficient. The impeding pedestrian per cycle volume and impeding pedestrian phase intervals were found to be significant parameters to assess efficiency of a permissive RTOAT FYA phase. Moreover, the research methodology assumed that the right-turn adjacent lanes green interval equals the PWI and FDW interval. In general, a permissive FYA phase was found low efficient at an impeding pedestrian total interval of less than 20 seconds and high efficient at an impeding pedestrian total interval equaling 25 seconds or longer when impeding pedestrian activity existed. A RTOAT FYA signal phase at 20 seconds impeding pedestrian is considered high efficient if the pedestrian volume per cycle is less than or equal 20 pedestrians per cycle. A BOS yield to pedestrians is strongly recommended during the impeding pedestrian intervals to warn the right-turn motorist to yield for pedestrians crossing the side street on a permissive RTOAT FYA signal phase.

CHAPTER 9: PERMISSIVE RIGHT-TURN FYA EFFICIENCY MODELING

9.1 Modeling Overview

The objective of the current section of the research is to develop a decision support system using discrete choice modeling to help decision makers to make a judgment that predicts the efficiency attributes for a permissive right-turn FYA signal. A discrete choice model might be used to predict a decision choice of an alternative from a set of alternatives (Koppelman and Bhat 2006). In the transportation field, a choice model could be used to predict a travel mode choice or destination choice for individuals or householders among several alternatives modes (Koppelman and Bhat 2006). I developed two multinomial logit MNL models to predict the efficiency of permissive right-turn FYA signal phases. The RTOIT and RTOILMNL models were developed to practically predict the efficiency attributes for the RTOIT FYA or the RTOIL FYA signal phases, and the RTOAT MNL model was developed to predict other efficiency attributes for a permissive RTOAT FYA signal phase.

9.2 Multinomial Logit Models Overview

Multinomial logistic regression was used to predict a categorical variable that was an alternative to a set of more than two alternatives (Starkweather and Moske 2011). The independent variables used to predict the response could be either binary or continuous. Multinomial logistic regression is an extended version of the binary logistic regression that predicts more than two alternatives of the dependent variable (Starkweather and Moske 2011). The MNL model "gives the choice probabilities of each alternative as a function of the systematic portion of the utility" of a set of alternatives (Koppelman and Bhat 2006). The probability expression of choosing an alternative 'i' (i =1,2,. . , J) from a set of J alternatives is:

$$Pr(Y_i = J - 1) = \frac{EXP^{\beta_1 . X_i}}{1 + \sum_{j=1}^{J-1} EXP^{\beta_j . X_i}} \qquad (2)$$

Where

Pr(i)= the probability of choosing an alternative i;

β_j= The parameter of an alternative j variable;

X_i= The observed value of an alternative j *variable*; and

J= The number of alternatives.

9.3 RTOIT and RTOIL Modeling Procedures

The stochastic results collected from the RTOIT and RTOIL DOEs were listed in one dataset that involves almost 800 observations in a set of random seeds replications. The dataset involves initially six independent variables and three categorical response variables. The pedestrian volume per cycle was assumed zero for all the RTOIL scenarios because the RTOIL DOE was designed without considering pedestrian volume as an independent variable. Furthermore, the dataset was built with a new categorical binary independent variable representing the impeding approach type to properly assess the potential performance difference between the RTOIT and the RTOIL FYA signal phases. The response, average MRTT per cycle, was categorized into three dummy variables represented as the nonefficient (NE), low efficient (LE), and efficient (E) categories. A multinomial logit model was developed to predict the efficiency attributes of a permissive RTOIT or RTOIL FYA signal phase using a number of parametric variables.

9.3.1 Variables Considered

The RTOIT and RTOIL efficiency attributes were predicted using a set of continuous and a categorical binary predictors. The impeding volumes were replaced by the impeding flow to capacity ratios (IFTCR) to accurately measure the impact of the impeding flow for any G/C signal plan. The impeding green interval, cycle length, pedestrian volume per cycle, and IFCTR were used as continuous variables. The impeding approach was listed as a categorical binary variable that represents the RTOIL FYA phase relative to the base category (RTOIT FYA phase). The MNL model results showed that the cycle length variable was statistically insignificant and correlated with other variables. Thus, it was dropped from the model's variables and consequently the pedestrian volume variable was listed in pedestrian per cycle instead of hour. The model development persuaders were undertaken initially for all variables and then by excluding any variable found statistically insignificant based on statistical significance (95% confidence level).

9.3.2 Model Estimation Results

The coefficients listed in Table 12 and Table 13 demonstrate the statistically significant effect of the listed variables on the RTOIT and RTOIL FYA efficiency attributes relative to the base category (NE). The model matrices and outputs are listed in Appendix E. The estimation results of variables are discussed in the following section.

Impeding green interval (IGI). The impact of impeding green on the RTOIT and RTOIL FYA phases efficiency attributes indicates that longer impeding green intervals improve the likelihood of applying an efficient FYA during the RTOIT and RTOIL phases. The impeding green intervals were statistically significant to predict the maximum right turn throughput on red phases (Tarko 2001, HCM 2010, Creasey, Stamatiadis et al. 2011) The model outcomes denote that the positive signed parameter for the impeding green interval increases the likelihood of implementing efficient or low efficient RTOIT or RTOIL FYA signal phases at longer impeding green intervals.

Impeding flow-to-capacity ratio (IFTCR). The effect of the impeding flow saturation ratio demonstrates that the RTOIT and RTOIL FYA phases are less likely to be efficient during a saturated impeding flow movement. Moreover, the RTOATR model outcomes indicate that the negative sign of the IFTCR parameter contributes to minimize the likelihood of efficient or low efficient RTOIT or RTOIL FYA signal phases as the IFTCR increases.

Impeding pedestrian volume per cycle. The impact of the impeding pedestrian volume per cycle indicates that the probability of efficient or low-efficient RTOIT and RTOIL FYA signal phases is less likely, especially at short impeding green intervals. The pedestrian activity was found to impede the right-turn movement and increase the total delay of an intersection (HCM 2010, Hurwitz, Monsere et al. 2018). Additionally, the MNL model outputs indicate that the impeding pedestrian volume per cycle negative signed parameter minimizes the probability of an efficient or low efficient RTOIT FYA signal phase when heavy pedestrian volume per cycle exists.

Impeding left-turn approach. The effect of the impeding left-turn approach indicates that the implementation of an efficient RTOIL FYA signal phase is less likely. The right-turn traffic was found more conservative in making a right turn on the RTOIL than the RTOIT. To conclude, the model outputs prove that the left-turn approach negative parameter decreases the probability of implementing an efficient FYA signal phase during the impeding left phase.

Table 11: RTOIT Efficiency MNL Model Estimates

Variables	Non-efficient (NE)	Low-Efficient (LE)		Efficient (E)	
		Estimate	T-stat	Estimate	T-stat
Constant	—	10.9629	5.122	13.4152	4.456
IGI	—	0.3765	8.755	1.0532	11.816
Pedestrian Per cycle	—	-0.3899	-6.725	-0.7021	-8.446
Left-turn Approach	—	-1.6735	-3.487	-8.8657	-7.892
IFTCR	—	-17.7709	-7.892	-44.2408	-10.442

Table 12: RTOIL Efficiency MNL Model Estimates

Mean log-likelihood =-0.2616	Non-efficient (NE)	Low-Efficient (LE)		Efficient (E)	
Variables	—	Estimate	T-stat	Estimate	T-stat
Constant	—	10.9629	5.122	13.4152	4.456
IGI	—	0.3765	8.755	1.0532	11.816
IFTCR	—	-17.7709	-7.892	-44.2408	-10.442
Left-turn Approach	—	-1.6735	-3.487	-8.8657	-7.892

9.4 RTOAT Modeling Procedures

The RTOAT dataset gathered 360 observations for the right turn on the adjacent through FYA signal phase. The observations were extracted from the RTOAT DOE scenarios in a set of random seeds replications. This step was undertaken to develop a decision support system that allows decision makers to assess the efficient application of a permissive FYA signal phase during the adjacent through green phase. The response, average MRTT per cycle, was categorized into two attributes representing the LE and E categories. The RTOAT MNL model was developed to predict the efficiency attributes for a permissive RTOAT FYA signal phase using a set of parametric variables.

9.4.1 Variables Considered

The RTOAT MNL model aimed to predict the efficient attributes of the RTOAT FYA signal phase using four parameters that involve the impeding pedestrian walk interval, the impeding FDW interval, the cycle length, and the pedestrian volume per cycle variables. A systematic process based on statistical significance of a 95% confidence level was undertaken to involve all independent variables. Then a procedure was taken by removing the statistically insignificant variables to achieve an accurate decision system model. The cycle length variable was statistically insignificant.

9.4.2 Estimation Results

The listed parameters in Table 13 show statistically significant variables that affect the efficiency attribute for a RTOAT FYA phase relative to the base attribute LE. The model matrices and outputs are listed in Appendix E. The parameters' coefficients are discussed in the following section.

Impeding pedestrian per cycle volume. The impact of pedestrian volume per cycle denotes that the implementation of a FYA signal phase is unlikely efficient when crowds of pedestrians exist. The negative sign for the pedestrian volume per cycle coefficient demonstrates that an intersection crowded with pedestrians crossing the side street likely reduces the probability of an efficient RTOAT FYA signal phase.

Impeding pedestrian total phase (PWI + FDW). Implementing a RTOAT FYA signal phase is more likely to be efficient at a long pedestrian phase. The impeding pedestrian PWI and FDW intervals were designed to fulfill a number of intersection geometric design conditions. The positive sign for the PWI and FDW parameters indicates the probability of implementing an efficient RTOAT FYA signal increased by lengthening the total pedestrian phase.

Table 13: RTOAT Efficiency MNL Model Estimates

Mean log-likelihood =-0.2616	Low-Efficient (LE)	Efficient (E)	
Variables	—	Estimate	T-stat
Constant	—	-23.4255	-4.947
Pedestrian Per cycle	—	-0.207	-5.906
PWI	—	1.2943	5.176
FDW	—	1.4312	5.597

The modeling procedures aimed to establish decision support systems. The response, average MRTT per cycle, was categorized in a couple dummy variables representing the efficiency of the permissive right-turn FYA phasing attributes. The observations were extracted from the DOEs scenarios in a set of random seeds replications. This step was undertaken to develop two decision support systems that allow decision makers to assess the efficient application of permissive FYA signal phases during the RTOIT, the RTOIL, and the RTOAT.

CHAPTER 10: CONCLUSION, FINDINGS, AND RECOMMENDATIONS

10.1 Research Summary and Discussion

The protected/permissive FYA signal allows functioning protected only mode, permissive only mode, protected/permissive mode, or a combination of the three signal indications modes. A protected right-turn phase allows right turners to make a protected right turn. The right turners on a permissive right-turn phase rely only on an acceptable gap between the impeding traffic, including bicycles and pedestrians, to maneuver (FHWA 2015). Understanding the right-turn phasing practices is an essential step toward warranting the permissive PPRT FYA signal phases. I reviewed right-turn phasing literature to properly develop permissive right-turn FYA signal phases' warrants. The DOEs were developed using a set of parametric variables including an impeding flow, an impeding green interval, a cycle length, and or pedestrian volume. Permissive right-turn signal phasing or right-turn FYA signal phasing warrants were not conducted in previous studies. Thus, this study was dedicated to developing the first permissive right-turn signal phases' warrants and a decision support system used to predict the efficient application of a right-turn FYA signal. The research conducted stochastic analysis to properly assess three permissive right turn FYA signal phases: RTOIT, RTOIL, and RTOAT. Every permissive right-turn phase was investigated in a separate systematical microsimulation analysis using a set of significant variables.

The developed DOEs investigated three permissive right-turn phases RTOIT, RTOIL, and RTOAT under a set of significant parameters. The permissive right-turn FYA phases were investigated in a stochastic analysis study to warrant an efficient right-turn FYA signal. The past studies stated that right-turn movements were significantly affected by the degree of saturation at certain approaches, arrival patterns, left-turn signal phasing on conflicting streets, and conflict with pedestrians and bicycles (McCoy, Ataullah et al. 1993, HCM 2010). The DOEs were developed using a set of parametric variables including an impeding flow, an impeding green interval, a cycle length, and a pedestrian volume.

The maximum right turn throughput was the main and only MOE used in the DOEs to assess the efficiency attributes for the permissive right turn FYA signal phases. The MRTT vph was used in many studies to predict the right turn capacity on a permissive right turn phase (Tarko 2001, Creasey, Stamatiadis et al. 2011). The warrants' development procedures were undertaken based on a certain site, hypothetical geometry designs, and listed DOEs input data (traffic vehicle features and signal timing parameters). The microsimulation analytical procedures were conducted using VISSIM version 10.02 software. VISSIM models were developed using both calibrated and noncalibrated hypothetical networks to investigate three permissive right-turn FYA signal phases.

Finally, I established discrete choice modeling procedures to develop a decision support system. The response, average MRTT per cycle, was categorized into a couple dummy variables representing the efficiency attributes for the permissive right-turn FYA signal phases. Almost one thousand observations were extracted from the DOEs scenarios in a set of random seeds used to develop two MNL models. This should help decision makers with predicting the efficiency attributes of permissive right-turn FYA signal phases on the RTOIT, the RTOIL, and the RTOAT.

Right-turn FYA signal phases might be coordinated with an adaptive signal timing control system. The impeding volumes can be estimated or predicted from the historic data (prior 2 or 3 cycles). Thereafter, internal calculations could be done to estimate the impeding green intervals and the IFTCR for a permissive right-turn FYA phase. However, the pedestrian count per cycle needs an assumption based on an intersection pedestrian demand. The developed MNL decision support system might be used as a logarithm installed on an adaptive signal controller to detect the efficient application of a right-turn FYA phase using a set of significant predictors and consequently change the mode of operation.

10.2 RTOIT Findings and Conclusion

The RTOIT research was dedicated to properly assessing the efficient implementation of a RTOIT FYA signal phase. The RTOIT FYA phase was efficient and highly recommended at an impeding green interval equal to 40 seconds or longer. The yield to pedestrian BOS is strongly recommended during an efficient FYA phase to alert right-turning motorists to yield for pedestrians walking concurrently with the impeding through traffic. The FYA phase on RTOIT mostly is not efficient at an impeding green interval of less than 15 seconds or an interval less than 25 seconds during a saturated impeding through approach. A red indication complimented with BOS of *No Turn on Red* on the impeding interval is strongly recommended during the non-efficient RTOIT phase. An impeding phase ranging from 30–35 seconds was found most likely low-efficient. The efficiency attribute of a low-efficient FYA phase is unlikely feasible through all cycles. Therefore, A Red indication might be implemented with No Turn on Red BOS during the low-efficient RTOIT FYA phase.

10.3 RTOIL Findings and Conclusion

The RTOIL experiment outcomes were unique and appropriately predicted the efficient implementation of a right-turn FYA signal phase during the impeding left phase. The impeding green interval and IFTCR were appropriate parameters to predict the efficiency of a RTOIL FYA signal phase. Overall, the RTOIL FYA signal phase was efficient only at an impeding interval equal to or more than 45 seconds. The RTOIL FYA phase was found NE at an impeding green interval less than 20 seconds and likely LE at an impeding green interval from 25–40 seconds. A red indication complemented with BOS of *No Turn on Red* is strongly recommended during a non-efficient RTOIL FYA phase. The right-turn on red RTOATR MNL model outcomes found that the efficiency attributes for the RTOIL significantly differ from the RTOIT. Exactly, the motorists on the permissive impeding left FYA phase were found more conservative in gap acceptance compared with RTOIT.

10.4 RTOAT Findings and Conclusion

The RTOAT experiment was conducted to efficiently warrant a right-turn FYA signal phase during the adjacent through lane phase. The literature indicated that the permissive right turn on circular green performance was not sufficiently researched. Thus, the RTOAT research primarily studied the significant variables that affect the permissive right-turn throughputs on a RTOAT FYA or a right-turn on circular green signal phase. I found that pedestrian volume and pedestrian phasing play a role significant to warrant the efficient use of a RTOAT FYA phase. Consequently, I developed functional right-turn FYA signal guidelines and a MNL model that helps decision makers to assess the efficiency of a RTOAT FYA signal phase using two pedestrian volume and phasing parameters. The research methodology assumed that the right turn adjacent lanes green interval equals the pedestrian total phase including the PWI and FDW intervals. To conclude, a permissive FYA phase was found low-efficient at an impeding pedestrian total interval less than 20 seconds and efficient at an impeding pedestrian total interval equal to or longer than 25 seconds. An RTOAT FYA phase at a 20-second pedestrian total interval is considered efficient if the pedestrians volume is less than or equal to 15 pedestrians per cycle. A right-turn FYA signal phase is highly recommended when an ideal efficient RTOAT FYA condition exists. A BOS yield to pedestrians is strongly recommended during the impeding pedestrian intervals to warn the right-turn motorist to yield to pedestrians crossing the side street. A Red indication might be implemented with No Turn on Red during the low-efficient RTOAT FYA phase.

10.5 Research Limitations and Future Studies

- The right-turn FYA signal phase warrants studied the right-turn FYA signal phases at an exclusive single lane. Thus, warrants for a right-turn FYA signal phases study at double right-turn lanes is highly recommended. Secondly, the RTOIT study assumed that the impeding flows are equally distributed through all impeding lanes. Thus, the impeding through approach was designed with exclusive through lanes and an exclusive right-turn long bay that separates the right-turn traffic from the impeding through lanes to maintain a uniform impeding flow at all lanes. Therefore, future study might assess the impact of an impending share rightmost lane on the right-turn FYA signal phase's efficiency performance.
- The RTOIL warrants study adopted only equal lanes at the impeding inbound left (eastbound to northbound) and the outbound northbound approaches. It is highly recommended to conduct a study on unequal inbound impeding left and outbound through lanes to investigate the potential impact of the lane's overlap on the rightmost lane. Intuitively, the overlap might be considered an impeding factor that worsen the RTOIL FYA signal phase performance.
- The microsimulation modeling used in VISSIM was coded to forbid pedestrians to start walking during the FDW phase, which might not replicate the real conditions at saturated pedestrian's signalized intersections. A pedestrian behavioral study should be conducted to further investigate the consistency between the pedestrian FDW phasing function used in VISSIM and real pedestrian behavior.

- Future research should be conducted to develop a proper logarithm that coordinates the adaptive signal control system and the right-turn FYA signal phases using the research outcomes and developed decision support systems.

APPENDIX A: THE EFFICIENT RTOIT FYA PHASE GUIDELINES

Table 14: The Efficient RTOIT FYA Phase Guidelines Obtained From the DOE

IFTCR	IGI= 20 s			IFTCR	IGI= 25 s		
	2 ppc	4 ppc	12 ppc		2 ppc	4 ppc	12 ppc
0.9	LE	LE	NE	0.85	LE	LE	NE
0.97	LE	NE	NE	0.93	LE	LE	NE
1.06	LE	NE	NE	1.01	LE	NE	NE
1.15	NE	NE	NE	1.10	NE	NE	NE

IFTCR	IGI= 30 s			IFTCR	IGI= 37 s		
	2 ppc	4 ppc	12 ppc		2 ppc	4 ppc	12 ppc
0.8	E	LE	LE	0.8	E	E	E
0.86	E	LE	LE	0.88	E	E	E
0.94	LE	LE	LE	0.96	E	E	LE
1.02	LE	LE	LE	1.03	E	E	LE

*NE represents a non-efficient FYA *LE represents a low efficient FYA *E represents an efficient FYA

Table 15: The Efficient RTOIT FYA Phase Guidelines Obtained From the DOE

IFTCR	IGI= 40 s			IFTCR	IGI= 45 s		
	2 ppc	4 ppc	12 ppc		2 ppc	4 ppc	12 ppc
0.8	E	E	E	0.75	E	E	E
0.86	E	E	E	0.84	E	E	E
0.95	E	E	E	0.92	E	E	E
1.02	E	E	E	1.0	E	E	E
IFTCR	**IGI= 50 s**			**IFTCR**	**IGI= 60 s**		
	2 ppc	**4 ppc**	**12 ppc**		**2 ppc**	**4 ppc**	**12 ppc**
0.75	E	E	E	0.73	E	E	E
0.85	E	E	E	0.8	E	E	E
0.91	E	E	E	0.88	E	E	E
1.01	E	E	E	0.95	E	E	E
*E represents an efficient FYA							

APPENDIX B: THE EFFICIENT RTOIL FYA PHASE GUIDELINES

Table 16: The Efficient RTOIL FYA Phase Guidelines Obtained From the DOE

IFTCR	IGI= 12 s	IFTCR	IGI= 15 s	IFTCR	IGI= 18 s
0.94	NE	0.87	LE	0.85	LE
1.15	NE	1.03	NE	0.97	NE
1.25	NE	1.17	NE	1.10	NE
1.3	NE	1.25	NE	1.20	NE
IFTCR	**IGI= 20 s**	**IFTCR**	**IGI= 22 s**	**IFTCR**	**IGI= 25 s**
0.85	LE	0.80	LE	0.78	LE
0.94	NE	0.95	LE	0.86	LE
1.05	NE	1.05	NE	0.94	LE
1.15	NE	1.10	NE	1.02	NE
IFTCR	**IGI= 30 s**	**IFTCR**	**IGI= 37 s**	**IFTCR**	**IGI= 45 s**
0.80	LE	0.78	E	0.75	E
0.88	LE	0.86	LE	0.84	E
0.95	LE	0.93	LE	0.90	E
1.02	NE	1.0	LE	0.97	LE

*NE represents a non-efficient FYA *LE represents a low efficient FYA *E represents an efficient FYA

APPENDIX C: THE EFFICIENT RTOAT FYA PHASE GUIDELINES

Table 17: The Efficient RTOAT FYA Phase Guidelines Obtained From the DOE

Ped. Walking Interval (s)	Pedestrians per cycle (ppc)	FDW = 10 s	FDW = 15 s	FDW = 25 s
PWI= 5 s	10	LE	E	E
	20	LE	E	E
	30	LE	LE	E
	40	LE	LE	E
PWI =10 s	10	E	E	E
	20	E	E	E
	30	LE	E	E
	40	LE	E	E
*LE represents a low efficient FYA *E represents the an efficient FYA				

APPENDIX E: THE MNL MODELS MATRICES AND OUTPUTS

THE RTOIT and RTOIL MNL MODEL MATRICES

	P01	P02	P03	P04	P05	P06	P07	P08	P09	P010
NE=	sero	sero	sero	sero	sero	sero	sero	sero	sero	sero
LE=	uno	sero	IMPGRN	sero	PEDSC	sero	IMPAPCH	sero	SATUR	sero
E=	sero	uno	sero	IMPGRN	sero	PEDSC	sero	IMPAPCH	sero	SATUR

THE RTOIT and RTOIL MNL MODEL Final OUTPUTS

	Mean log-likelihood =-0.2616			
Variable Name	Variable code	Coeff	SE	T-stat
Constant 0	P01	10.9629	2.1403	5.122
Constant 1	P02	13.4152	3.0105	4.456
IMPGRN	P03	0.3765	0.043	8.755
IMPGRN	P04	1.0532	0.0891	11.816
PEDSC	P05	-0.3899	0.058	-6.725
PEDSC	P06	-0.7021	0.0831	-8.446
IMPAPCH	P07	-1.6735	0.4799	-3.487
IMPAPCH	P08	-8.8657	1.1234	-7.892
SATUR	P09	-17.7709	2.2062	-7.892
SATUR	P10	-44.2408	4.2367	-10.442

THE RTOAT MNL MODELS MATRICES

	P01	P02	P03	P04
LE=	sero	sero	sero	sero
E=	Uno	PEDC	WLK	FDW

THE RTOATR MNL MODELS Final OUTPUTS

	Mean log-likelihood =-0.2616			
Variable Name	Variable code	Coeff	SE	T-stat
Constant 0	P01	-23.4255	4.7353	-4.947
PEDC	P02	-0.207	0.0351	-5.906
WLK	P03	1.2943	0.25	5.176
FDW	P04	1.4312	0.2557	5.597

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